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ENGINEERING • SYSTEMS ANALYSIS • ENVIRONMENTAL SYSTEMS • SUPPORT SERVICES

ASSESSMENT OF THE AVAILABILITY OF THE TRACKING AND DATA RELAY SATELLITE SYSTEM FOR LANDSAT MISSIONS

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SECTION 1. INTRODUCTION

1.1 SCOPE

This report presents the results of an investigation of the telecommunications availability that can realistically be provided by the Tracking and Data Relay Satellite System (TDRSS) for Landsat D type missions. Although the assessment focusses on the telecommunications requirements of the near Earth orbit missions of the 1985 - 1989 time frame, it emphasizes Landsat D and its competing demand for wideband, real-time RF link services from TDRSS. Limitations in availability of communications services are identified, including systematic TDRSS restrictions, conflicting telecommunication requirements and loading problems of all users (missions) which are to be supported by TDRSS. Also, several telecommunications alternatives for Landsat D utilization independent of TDRSS services are discussed.

1.2 BACKGROUND

1.2.1 THE TDRSS CONCEPT

NASA's telecommunications needs in the 1980's are being supported by the Tracking and Data Relay Satellite System (TDRSS) which will consist of two geostationary relay satellites 130 degrees apart in longitude (Figure 1-1) and a ground station located at White Sands, N.M. (Figure 1-2). In its final configuration the system will also include two spare satellites, one parked in orbit and one posed for a rapid replacement launch. This system will provide communications and tracking services between low Earth orbiting user spacecraft (i.e., Landsat, Shuttle) and telecommunications control and/or data processing facilities on the ground. TDRSS has been designed around a real-time, bent-pipe concept enabling the operation of a wide variety of telecommunications services. This system provides no processing of user data. However, the system will be capable of transmitting data to, receiving data from, or tracking user spacecraft over a large percentage of the user orbit.

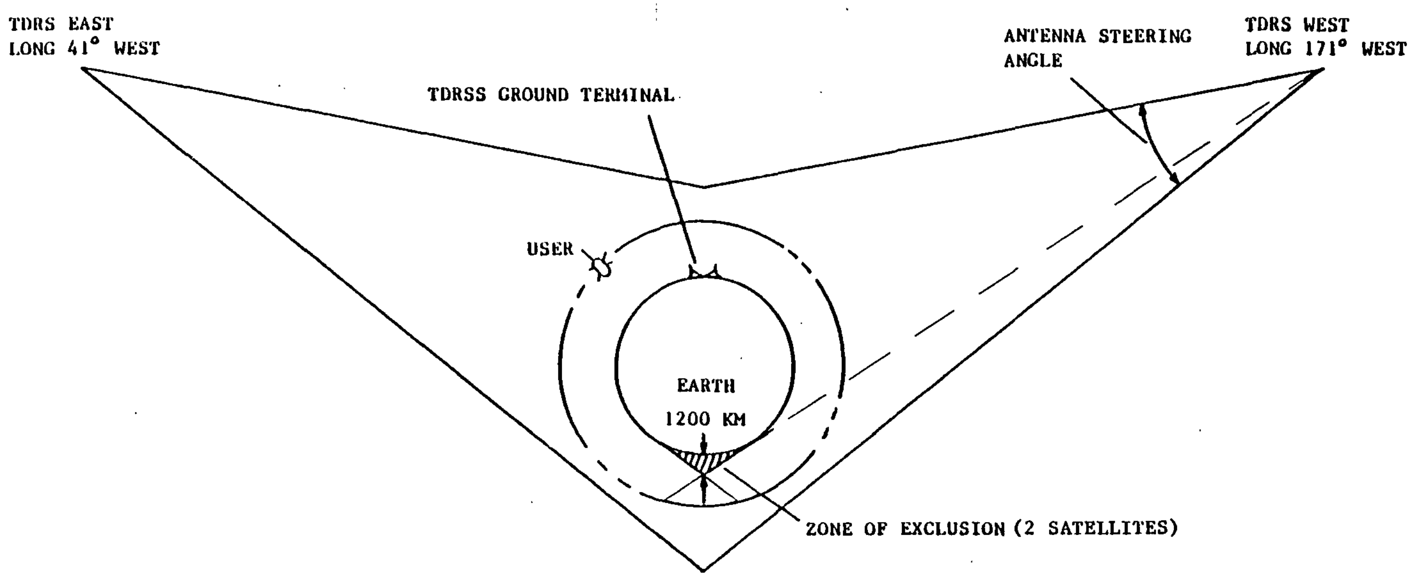


Figure 1-1. Tracking and Data Relay Satellite System

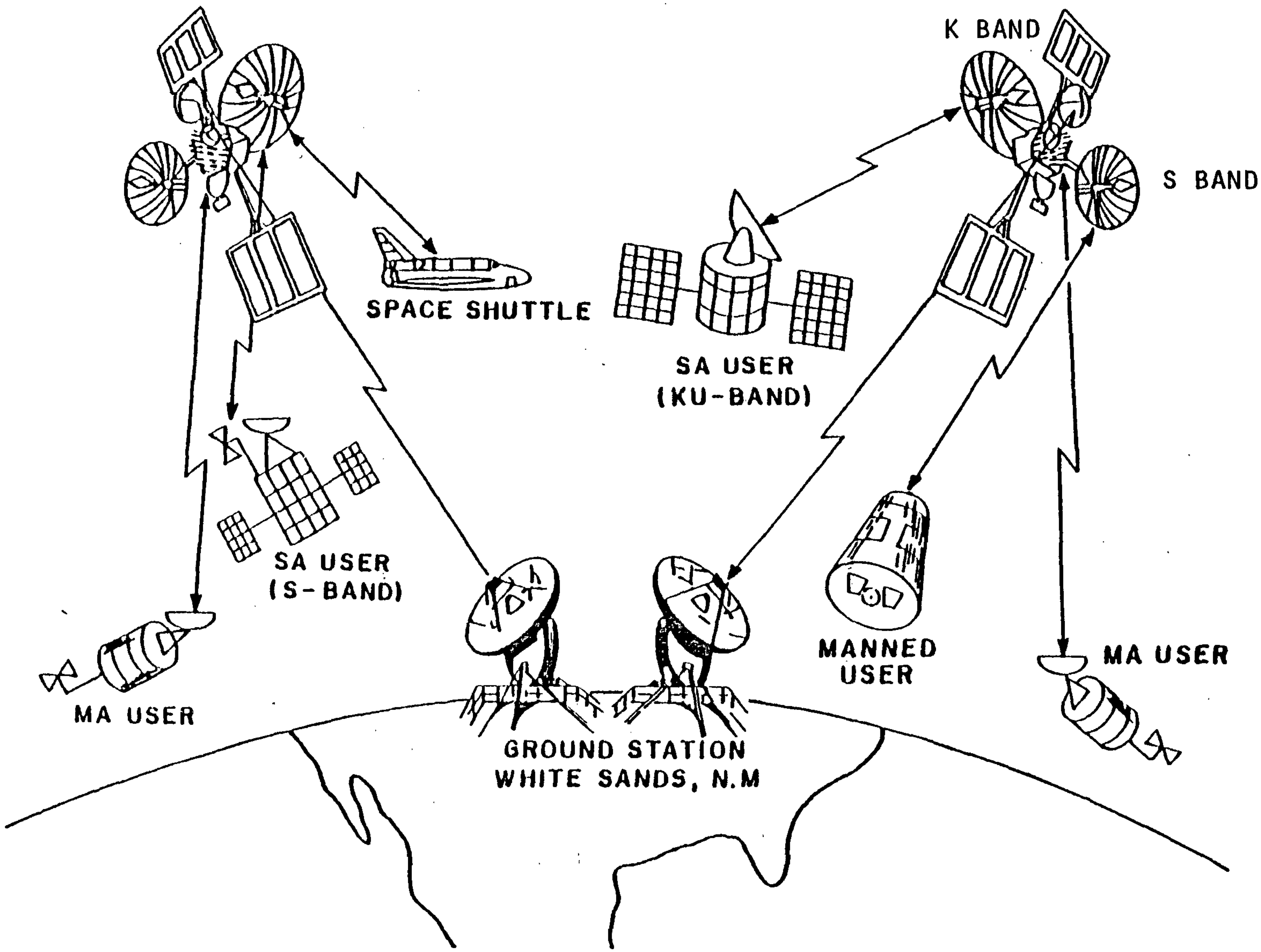


Figure 1-2. TDRSS/User Configuration

1.2.2 TDRSS SERVICES

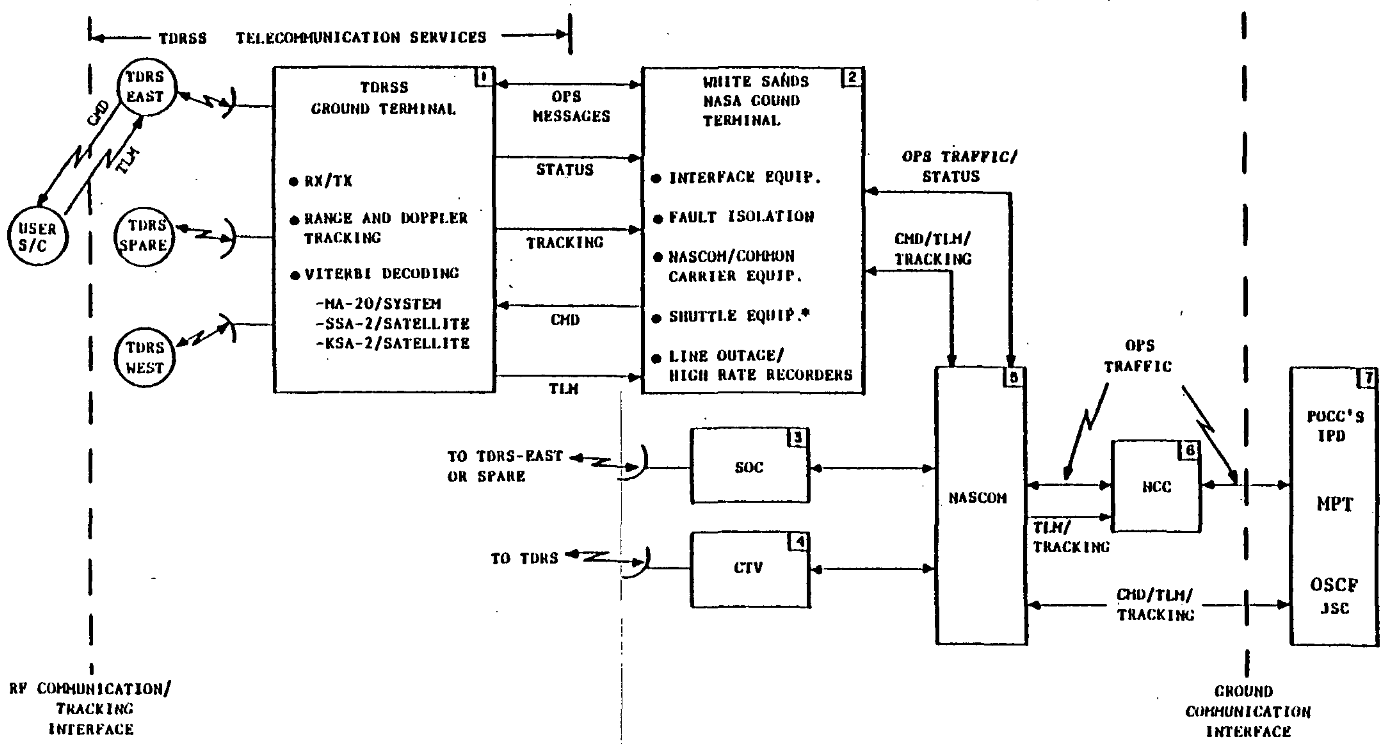
TDRSS will provide Communications and Tracking (C&T) services to approved users. Forward link services from the ground station to the user spacecraft include tracking and command data channels at S-band and K-band frequencies. Return link services from the user spacecraft to the ground station include a tracking channel and telemetry data channels accomodating a wide range of data rates. These return link services are available at S-band and K-band frequencies. S-band forward and return link services are provided via Single Access (SA) and Multiple Access (MA) service. SA service uses steerable parabolic antennae on the individual Tracking and Data Relay Satellite (TDRS), while the MA Service utilizes an array antenna with ground-implemented phasing. K-band forward and return link services are available for SA only.

1.2.3 TDRSS AND STDN

Communications with and tracking of user spacecraft are currently performed by the Spaceflight Tracking and Data Network (STDN). It consists of a network of worldwide ground-based tracking stations and supporting elements which perform network control, monitoring, fault isolation, data transfer, compatability testing and simulation. The TDRSS C&T Network (Figure 1-3), when it becomes operational in late 1982, will provide C&T services for all NASA low-Earth orbiting missions.

1.2.4 LANDSAT D

As one of the first users of TDRSS, the LANDSAT D project has been planned with a real-time C&T system in mind. Thus the spacecraft is provided with standard narrow-band tape recorders for storing and receiving engineering data, but no onboard image recording capability is provided. The Landsat project expects to use TDRSS support fully as soon as it is available.



*Interim capability

Figure 1-3. TDRSS C&T Network

For preliminary planning purposes, the TDRSS loading for a single Landsat D spacecraft has been estimated to be as follows:

MA Service: One return link contact per orbit of 20 minutes duration for real time telemetry and ranging data.
One forward link contact every third orbit of approximately 15 minutes duration for command and ranging.

SSA Service: Approximately 17 contacts per day averaging 15 minutes each for readout of several spacecraft telemetry channels (these contacts are not coincident with MA support).

KSA Service: Approximately two contacts per orbit averaging 7 minutes in duration. These KSA contacts are coincident with either MA or SSA support periods for imagery, MSS and/or TM.

1.3 INVESTIGATION GROUND RULES

This investigation was focussed on the communications and tracking service requirements of near Earth orbit missions in the 1985-1989 time frame. Of these missions only Shuttle missions and the Landsat D and D' could be identified as having simultaneous demands for wide-band link services from TDRSS. In order to understand the potential impact of these demands, these missions have been subjected to a detailed real-time communications requirements analysis for those services that will be available throughout the Landsat missions. Competing and/or conflicting requirements for TDRSS service by the Landsat D mission have been identified and their impact on Multispectral Scanner (MSS) and Thematic Mapper (TM) image availability are discussed. The configuration of the two TDRS relays in orbit and the location of the TDRSS ground station at White Sands, N.M. are providing fixed zones of visibility and a zone of exclusion (ZOE). The orbital instantaneous position of user satellites indicates which TDRS could provide an RF link to the ground station. Thus the prerequisites for TDRSS availability depend on (1) user satellite visibility to one and/or two or none of the two TDRS'S, (2) the examiniation of service priorities and clarification of competing multiple satellites (Landsat and others for the same TDRS), (3) the resolution of detailed data transmission schedules (timing and data acquisition periods) inclusive of link acquisition time.

1.4 APPROACH TO THE INVESTIGATION

This investigation was undertaken in four phases. In the first phase the Landsat D and D' telecommunications requirements have been determined by analysis of an orbital flight model which replicated the characteristics of Landsat D and D'. Based on these orbital characteristics, the ground track coverage and timing for possible MSS and TM real-time data communications to the ground were calculated. Possible TDRSS loading was determined by calculation of the times at which Landsat is over a landmass during descending (daylight) orbits and over non-polar regions (i.e., $\pm 80^{0}$ latitude). Night time data acquisition by the TM thermal IR band was not included in this analysis. Based on the findings of phase I the Landsat D loading requirements of each TDRS were determined.

In Phase II the telecommunication requirements of non-Landsat TDRSS users were determined. In addition to the Landsat demands (requirements) for telecommunications links, other TDRSS users have similar requirements of their own. By appropriate computer-based modelling of the orbital characteristics of the Shuttle flights, the user requirements for telecommunications services as a function of time and required kinds of services were determined. Thus a TDRSS wide-band link demand schedule can be prepared for the Resource Observation missions planned for the 1985-1989 period.

In Phase III the results of the analysis carried out in phases I and II were overlaid on the same time base. Since the Shuttle missions are considered as manned space missions, they have by definition, telecommunications priority for all available TDRSS services including wide band services. Thus correlation of the telecommunications link demands as had been defined in Phases I and II have provided a profile of possible (worst case) contested link services. Systematic TDRSS restrictions of link services, such as those caused by the zone of exclusion when neither of the two TDRS's can be accessed by the user spacecraft, have been identified.

In Phase IV, telecommunications alternatives for mission utilization independent of TDRSS services has been discussed. Thus this task has identified work arounds which would allow the acquiring of Landsat data when a higher priority mission preempts TDRSS and/or systemmatic

restrictions preclude TDRSS services. The relationship of state-of-the-art technology and timely availability to Landsat users was factored into the considerations of the alternatives which are discussed. The effect of the planned phase-down and consolidation of the Ground Spacecraft Tracking and Data Network (GSTDN) and the Deep Space Network (DSN) on telecommunications alternatives has also been considered in some detail.

SECTION 2. LANDSAT D and D' TELECOMMUNICATION REQUIREMENTS

As a first cut at determining the Landsat D and D' telecommunications requirements, the operating practices for Landsat 1, 2, and 3 were examined with a view toward determining their applicability to Landsat D and D'. Such an examination had been made in the preparation of the Support Instrumentation Requirements Document (SIRD). The level of detail available, however, made it impracticable to use these data for detailed identification of conditions under which two missions (e.g., a Landsat D-type mission and the Space Shuttle) could be competing for TDRSS support. There is a major difference in the orbits of Landsat D and D' as compared to the earlier missions which also makes it impracticable to use Landsat 1, 2, and 3 data for the present study. The image location for Landsat 1, 2, and 3 are specified in terms of a "Worldwide Reference System" (WRS) which makes use of the 14-day repeat cycle of these spacecraft illustrated in Figure 2-1. The repeat cycle for Landsat D and D' is sixteen days. A WRS for Landsat D and D' was not available when the investigation was started; OAO found it necessary to generate these data in-house.

2.1 LANDSAT ORBITAL DIFFERENCES

The differing characteristics of the orbits planned for Landsat D and D' as compared to Landsat 1, 2, and 3 are shown in Table 2-1. The lower altitude of Landsat D, and its shorter period lead to full earth coverage in 233 orbital revolutions over a repetition period of 16 days, as compared to 251 revolutions and 14 days for Landsat 1, 2, and 3. There are differences, too, in the way in which the orbital swaths are laid down from day to day. For Landsat 1, 2, and 3, as shown in Figure 2-2, successive orbits on a given day are separated by 2872 km at the equator. On the following day the orbital progression is shifted westward by 159 km (as measured at the equator), a shift which provides 14% sidelap (at the equator) with adjacent imagery such as is obtained by the MSS with its 185 km scan (Figure 2-3). The image size for Landsat D is the same as for the earlier 3 Landsats.

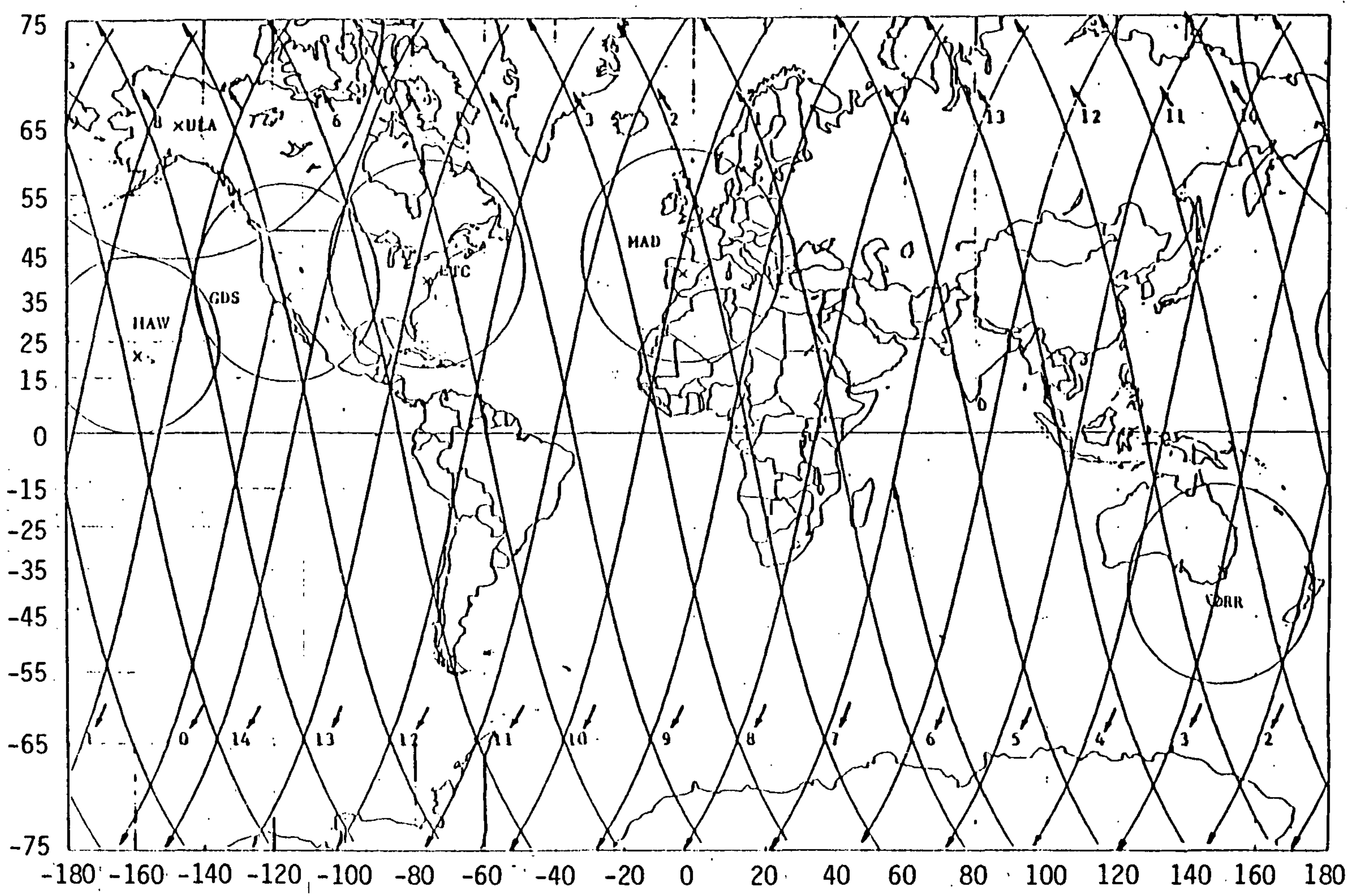


Figure 2-1. Typical One Day Geographic Coverage for Landsat 1, 2 and 3

Table 2-1. Orbital Characteristics of Landsat 1, 2, 3 and D

PARAMETER	SATELLITE 1	2	3	D
Nominal Altitude (km)	907.299	907.849	907.636	705.325
Semi-major Axis (km)	7285.438	7285.989	7285.776	7083.465
Inclination (deg)	99.906	99.210	99.117	98.22
Period (min.)	103.143	103.155	103.150	98.9
Time of Descending Node Equatorial Crossing (local time)	8:50 AM	9:08 AM	9:31 AM	9:45 AM
Separation of Successive Nodes (km)	2872	2872	2872	2752
Coverage Cycle Duration (days)	18	18	18	16
Revolutions per Coverage Cycle	251	251	251	233
Distance Between Adjacent Ground Tracks at Equator (km)	159.38	159.38	159.38	172

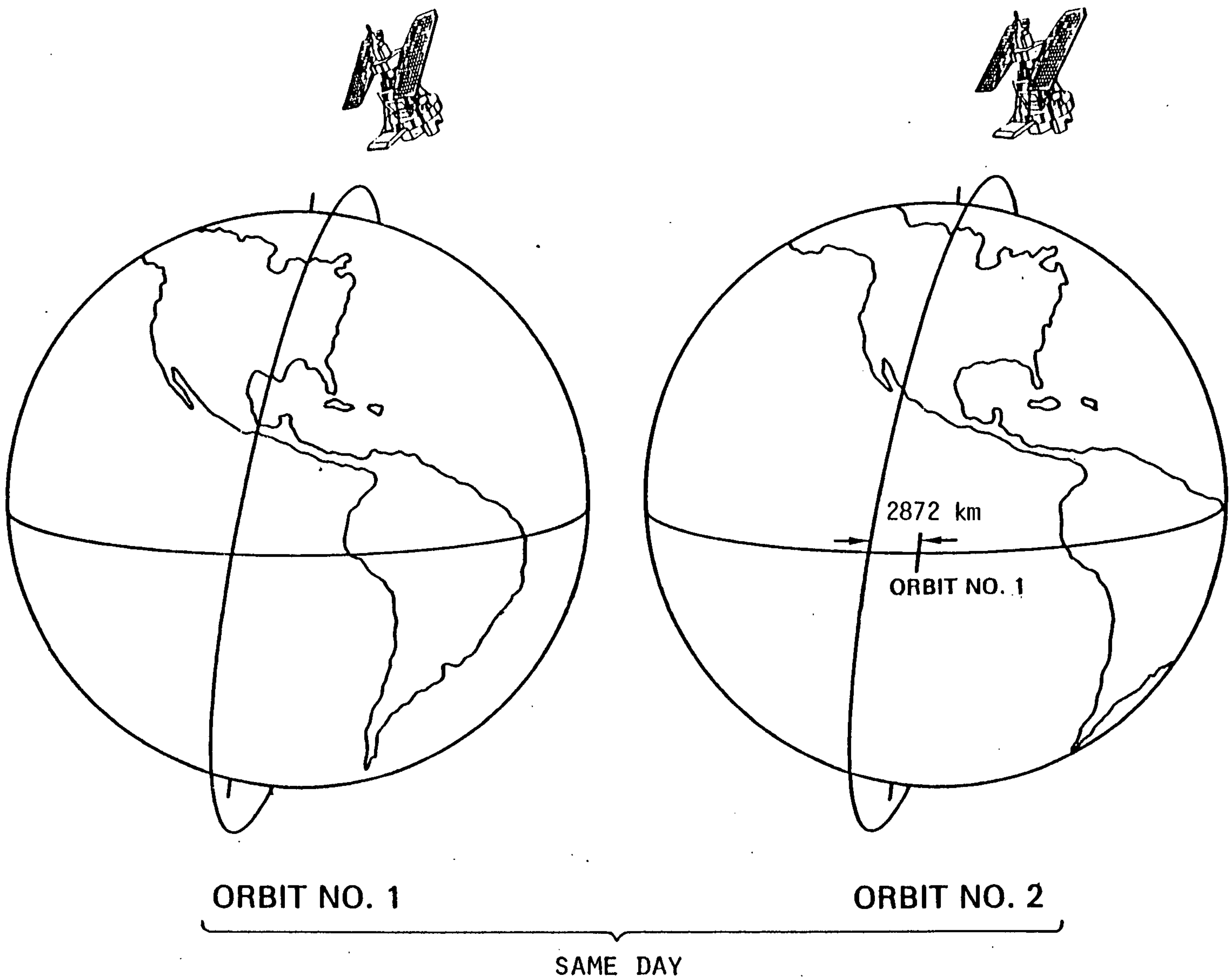


Figure 2-2. Landsats 1, 2, and 3 Successive Ground Coverage

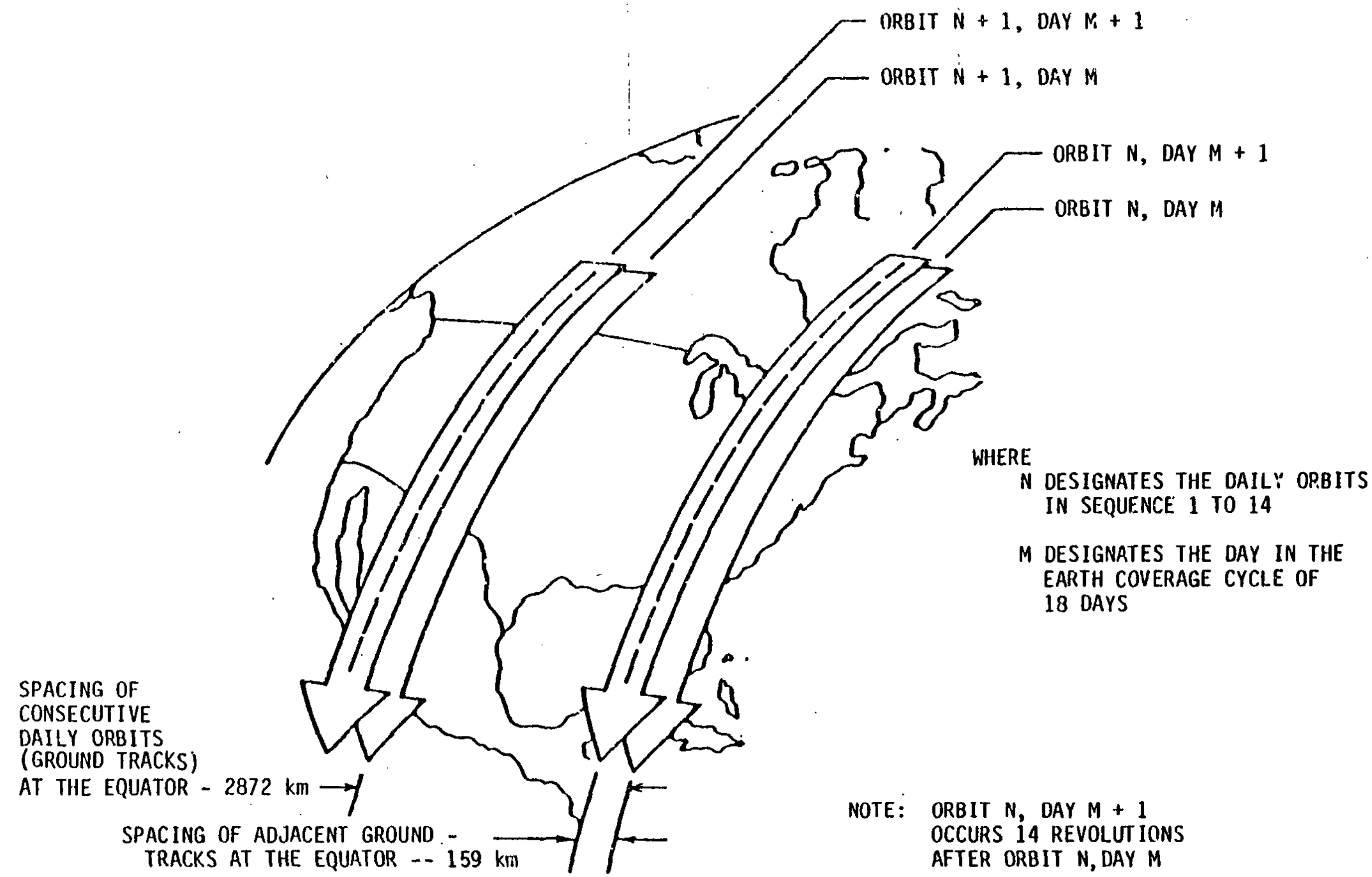


Figure 2-3. Landsats 1, 2, and 3 Consecutive Day Ground Coverage Pattern

For Landsat D, successive orbits are separated by 2752 km at the equator (see Figure 2-4) while on the next day the pattern is shifted westward by 1204 km, as shown in Figure 2-5. Adjacent imagery is achieved on the 8th day, when "adjacent" path centers are separated by 172 km at the equator. The Landsat D swathing pattern is illustrated in more detail in Figure 2-6, which illustrates the orbital progression from Day 1 through Day 16, during which time the entire earth can be seen by the Landsat D imagers. During the full 16-day period, adjacent orbital paths occur in the progression shown in Table 2-2. Assuming that a World Reference System like that for Landsat 1, 2, and 3 is established for Landsat D and that there are 233 paths numbered westward around the earth from 1 to 233, then if on a given day paths 106, 122 --- 97 are covered, on the next day paths 97, 113, --- 104 will be covered, and so on as shown through the full 16-day cycle.

2.2 DETERMINATION OF DETAILED TELECOMMUNICATIONS REQUIREMENTS

Landsat D will require a communications link to transmit the scientific data observed with the multispectral scanner (MSS) or thematic mapper (TM). To know when these links will be required, from day to day and for how long, demands a knowledge of Landsat's observing schedule, which until launch can only be estimated using the following assumptions.

First, Landsat will observe only in the non-polar regions. Observations of the oceans and the ice caps are not germane to Landsat's scientific objectives.

Second, due to the spectral bands observed with Landsat instruments, observations will be taken primarily in daylight, i.e., during the descending half of the planned orbit.

A third assumption made in this exercise is that Landsat D, not having data storage capability, will transmit its data as it observes, i.e., in real-time.

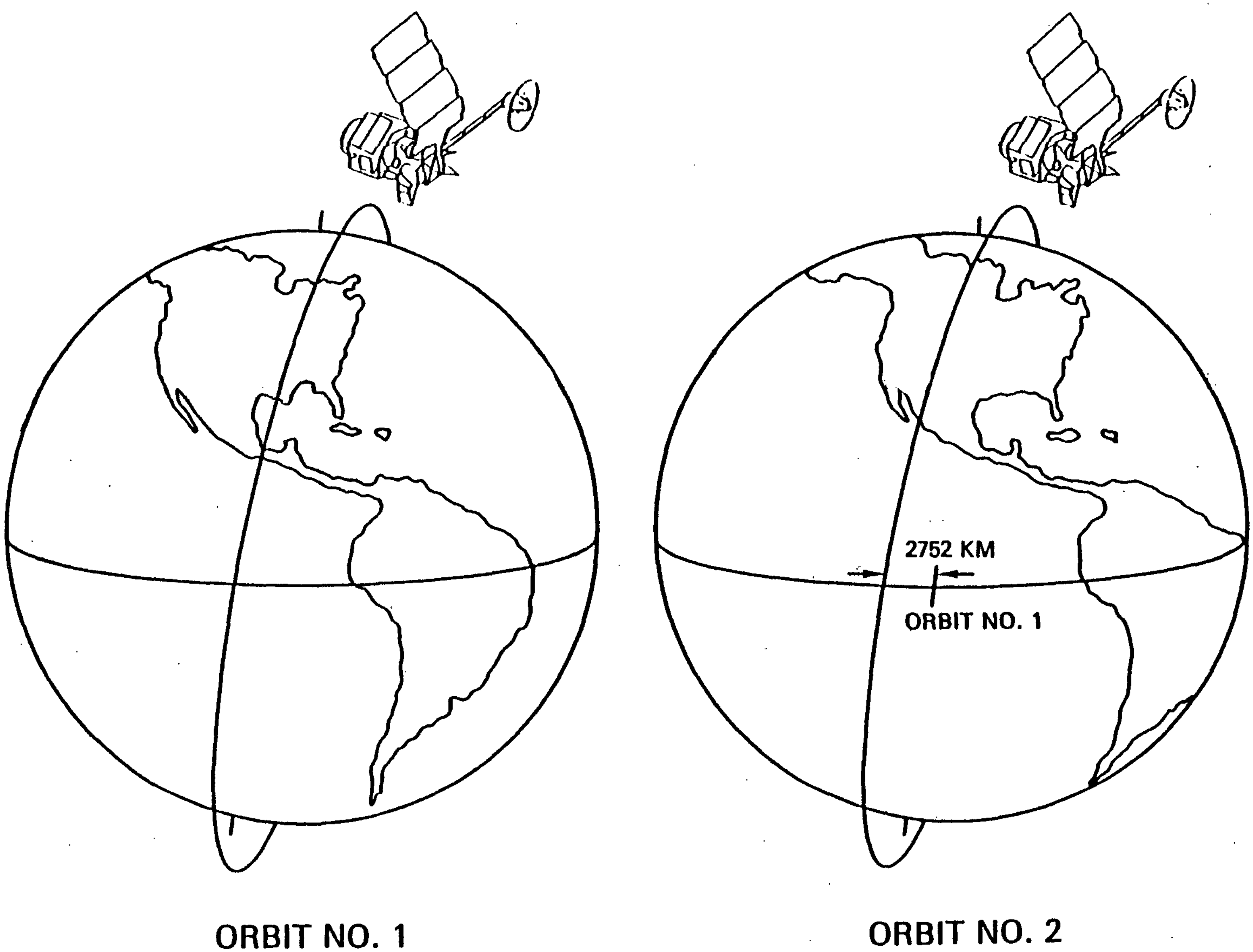


Figure 2-4. Landsat D Typical Successive Daily Ground Tracks

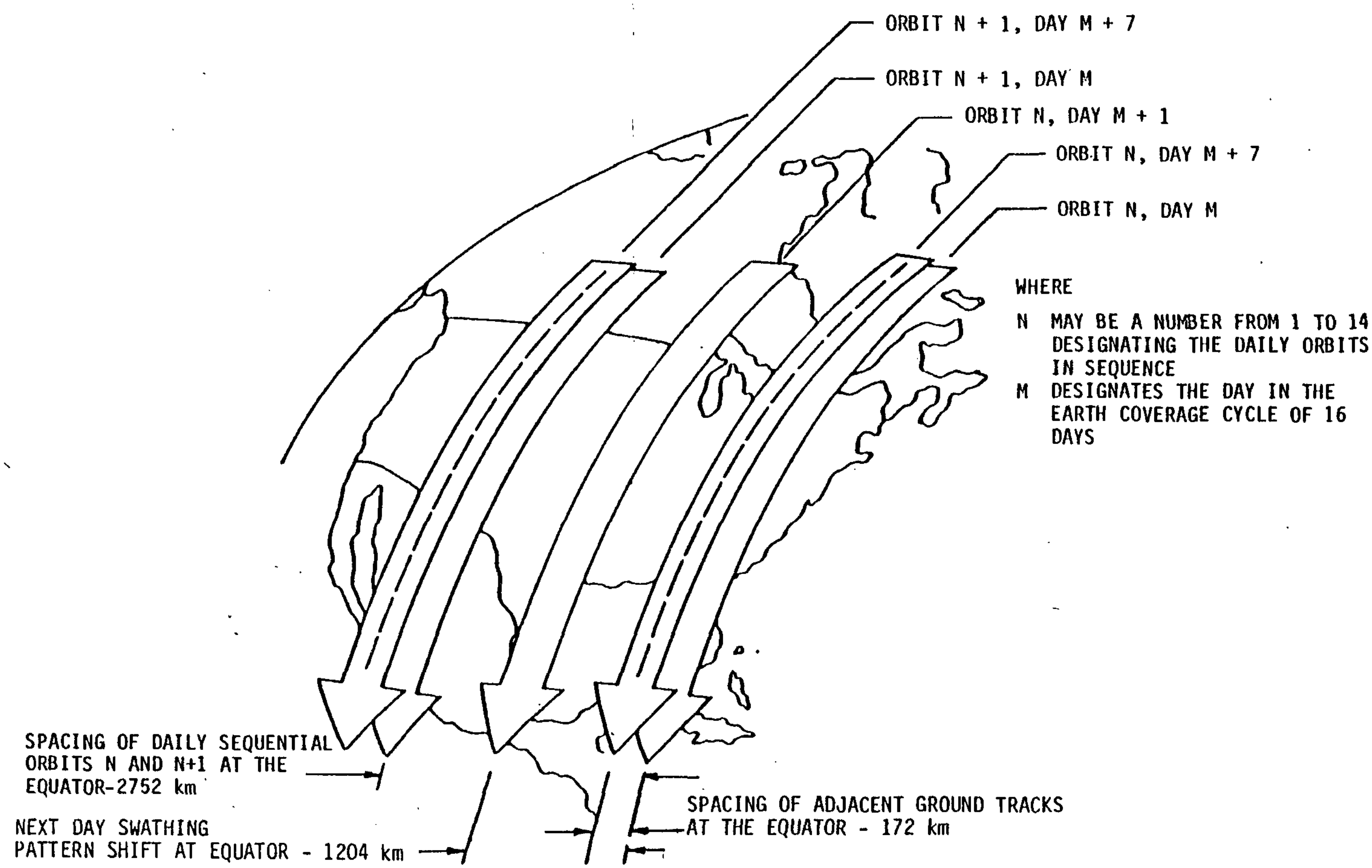


Figure 2-5. Landsat D Ground Coverage Swathing Pattern

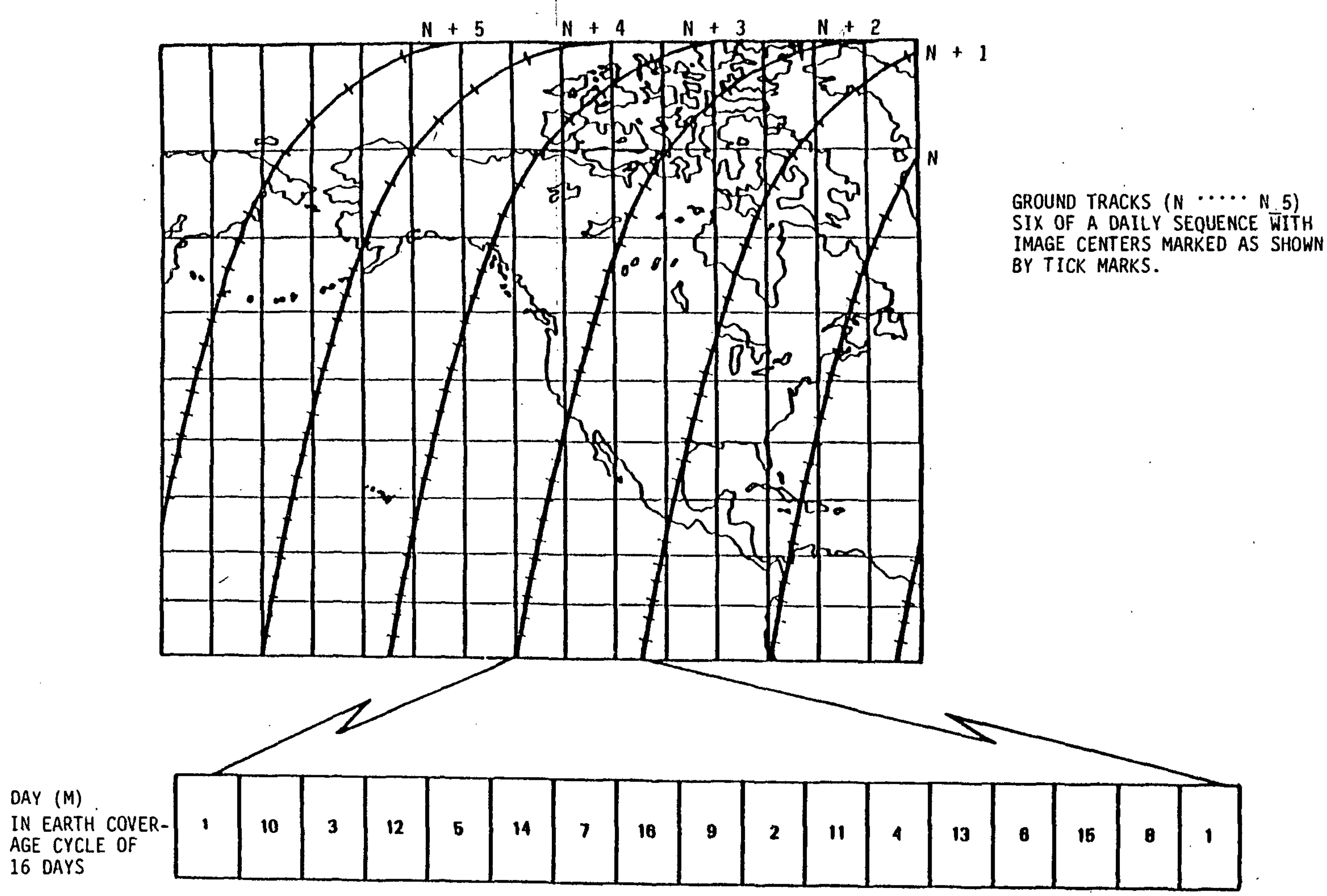


Figure 2-6. Landsat D Swathing Pattern and Staggered Daily Sequence of Ground Tracks of Complete 16 Day Coverage Cycle

Table 2-2. Landsat D Orbit/Path Sequence

Cycle Day	Path Numbers*
1	106, 122, 138, 154, 170, 186, 202, 218, 1, 17, 33, 49, 65, 81, 97
2	97, 113, 129, 145, 161, 177, 193, 209, 225, 8, 24, 40, 56, 72, 88, 104
3	104, 120, 136, 152, 168, 184, 200, 216, 232, 15, 31, 47, 63, 79, 95
4	95, 111, 127, 143, 159, 175, 191, 207, 6, 22, 38, 54, 70, 86, 102
5	102, 118, 134, 150, 166, 182, 198, 214, 230, 13, 29, 45, 61, 77, 93
6	93, 109, 125, 141, 157, 173, 189, 205, 221, 4, 20, 36, 52, 68, 84, 100
7	100, 116, 132, 148, 164, 180, 196, 212, 228, 11, 27, 43, 59, 75, 91
8	91, 107, 123, 139, 155, 171, 187, 203, 219, 2, 18, 34, 50, 66, 82, 98
9	98, 114, 130, 146, 162, 178, 194, 210, 226, 9, 25, 41, 57, 73, 89, 105
10	105, 121, 137, 153, 169, 185, 201, 217, 233, 16, 32, 48, 64, 80, 96
11	96, 112, 128, 144, 160, 176, 192, 208, 224, 7, 23, 39, 55, 71, 87, 103
12	103, 119, 135, 151, 167, 183, 199, 215, 231, 14, 30, 46, 62, 78, 94
13	94, 110, 126, 142, 158, 174, 190, 206, 222, 5, 21, 37, 53, 69, 85, 101
14	101, 117, 133, 149, 165, 181, 197, 213, 229, 12, 28, 44, 60, 76, 92
15	92, 108, 124, 140, 156, 172, 188, 204, 220, 3, 19, 35, 51, 67, 83, 99
16	99, 115, 131, 147, 163, 179, 195, 211, 227, 10, 26, 42, 58, 74, 90, 106

*Referenced to Landsat-D world reference system (WRS).

2.2.1 GROUND TRACK DETERMINATION

Following the assumptions that Landsat will observe only land areas, the satellite's ground track must be determined in sufficient detail to indicate when and for how long, the instruments (which observe satellite nadir), will have land in sight. The ground track is determined by a computer program which calculates for time (t) the satellite's orbital position referenced to the earth's latitude-longitude system assuming a circular Keplerian orbit around a spherical earth.

The program assumes a rotating vector of constant (unit) length (i.e., a circular orbit) transformed through the matrix for the earth's coordinate system. The circular orbit is assumed subject to no perturbations (e.g., atmospheric drag and gravity anomalies) since the maintenance of the satellite in its nominal orbit will minimize perturbation effects. The program requires the following input: the orbital characteristics of altitude, inclination, and period; initial time; initial position in latitude and longitude, and earth rotation rate relative to the (precessing) orbit plane.

For this exercise, initial time, latitude, and longitude were all assumed zero; and the orbital characteristics of Landsat D as shown in Table 2-1 were used.

The program was created in BASIC to run on the Commodore personal minicomputer. It was later translated to FORTRAN for the VAX/VMS. The derivation of the program, and its listings, are included as Appendices A, B, and C.

2.2.2 POSTULATED LANDSAT D OBSERVATION SCHEDULE

The program result is a printout of satellite position, in latitude and logitude, as a function of time. These data were plotted on a global Mercator map for the entire 233-orbit Landsat cycle to generate a postulated Landsat D ground track. Time was noted on the ground track by marking 2-minute intervals.

This exercise allowed determination of a postulated Landsat observation schedule, from which the detailed telecommunication requirements may be

derived. The observation schedule is a 23,040-minute (16 days) timeline, on which are marked the intervals when the ground track encounters and passes over a land mass. The observation interval was assumed to begin at the nearest minute before the ground track actually encounters land and to continue unitl the nearest minute when the ground track is no longer over land. All land masses between $\pm 80^{0}$ latitude were considered as observation targets, including large and small islands and peninsulas as well as continents. Bodies of water which took less than one minute to cross were ignored; consequently objects such as rivers and even large lakes are included in the Landsat observation schedule.

Since the orbit program calculated only a possible Landsat cycle, the details of the observation schedule, such as observing Australia on the first day of the cycle, are unlikely to hold true after launch. However, the length and number of the observation intervals are unlikely to change; that is, Australia will still be observed a certain number of times, and each time the observation interval will be 5 or 6 minutes long. Therefore the observation intervals for one complete coverage cycle (16 days) were grouped by length and summarized in a frequency distribution plot (histogram).

The frequency distribution plot in Figure 2-7 is the result. The observation intervals represent time spent observing targets as described in the preceding paragraph. There are 476 intervals per coverage cycle, ranging from less than one minute to 30 minutes, and totaling 3270 minutes for each 16 days

From this plot can be determined the typical characteristics of the real Landsat observation schedule, no longer restricted to the postulated schedule of the computer run. For example, Landsat could observe and relay a total of 3270 minutes of data every 16 days. It will not observe all 3270 at once, but in intervals averaging 7 minutes in length, although it will more commonly observe for shorter intervals. Of these shorter intervals, 145 or 30 percent are 2 minutes or less, illustrating the profusion of islands, peninsulas, and isthmuses on the world map.

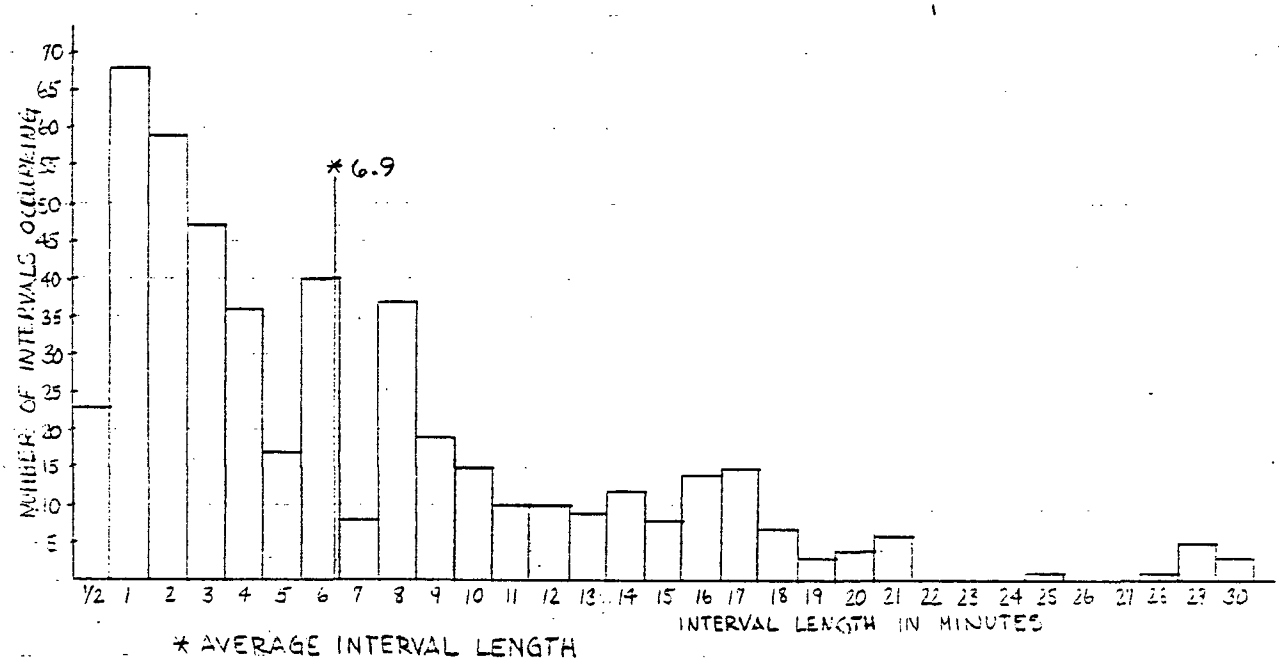


Figure 2-7. Frequency Distribution of Landsat D Observation Intervals During One 16-Day Cycle

The only characteristics not apparent in Figure 2-7 are those relating to orbits. These are listed in Table 2-3 which shows that, on the average, Landsat will observe twice during one orbit for 7 minutes each time (14 minutes total). The minimum observation in one orbit is zero (no encounter of land masses); the maximum is 30 minutes. The minimum number of observation intervals per orbit is zero and the maximum is five.

A final characteristic of the Landsat D observation schedule is again not apparent in Figure 2-7, but must be generalized from the entire postulated schedule of the complete coverage cycle. That generalization is this: Landsat observation is concentrated in 30-minute intervals of activity, followed by 70 minutes of no activity. This characteristic is a function of the polar orbit and the requirement to observe only daylit, non-polar land areas.

2.3 POSSIBLE LINK AVAILABILITY OF TDRSS

For the purpose of the Landsat mission, with its 85 megabit science data rate, the TDRSS may be considered to consist of two geosynchronous satellites, TDRS-E and TDRS-W, each with two single access (KSA) wideband links. Nominally, the relay satellites will be placed at altitudes of 35,800 km near the earth's equatorial plane, one at 171^{O} W longitude (TDRS-W) and one at 41^{O}W longitude (TDRS-E).

The primary condition for a satellite's link availability with TDRSS is visibility, which is a simple plane geometry problem with the Earth introducing an obscuration where the only variable is the altitude of the user spacecraft. Figure 2-8 is a graphic representation of the problem.

For TDRS-E at 41^{O}W, its view of Landsat D is obscured by the earth when Landsat is viewing a region approximately 73^{O} in radius centered on the equator opposite the TDRS-E subsatellite point, i.e. 139^{O}E. TDRS-W has a similar shadow zone, centered on the equator at longitude 9^{O}E. These two shadow zones overlap, forming a zone of no coverage, called the Zone of Exclusion (ZOE). The two shadow zones and the ZOE are plotted on a global map in Figure 2-9. When a Landsat D satellite is over the convex lens-shaped area centered on longitude 74^{O}E, neither member of the TDRSS pair

Table 2-3. Observation Opportunities for Landsat D

	Per Cycle	Per Day (Average)	Per Orbit (Average)	Maximum Uninterrupted	Minimum
Data Acquisition/ Observation Times (min)	3270	204.4	14	30	0
Number of Observation Intervals	476	30	2	5	0

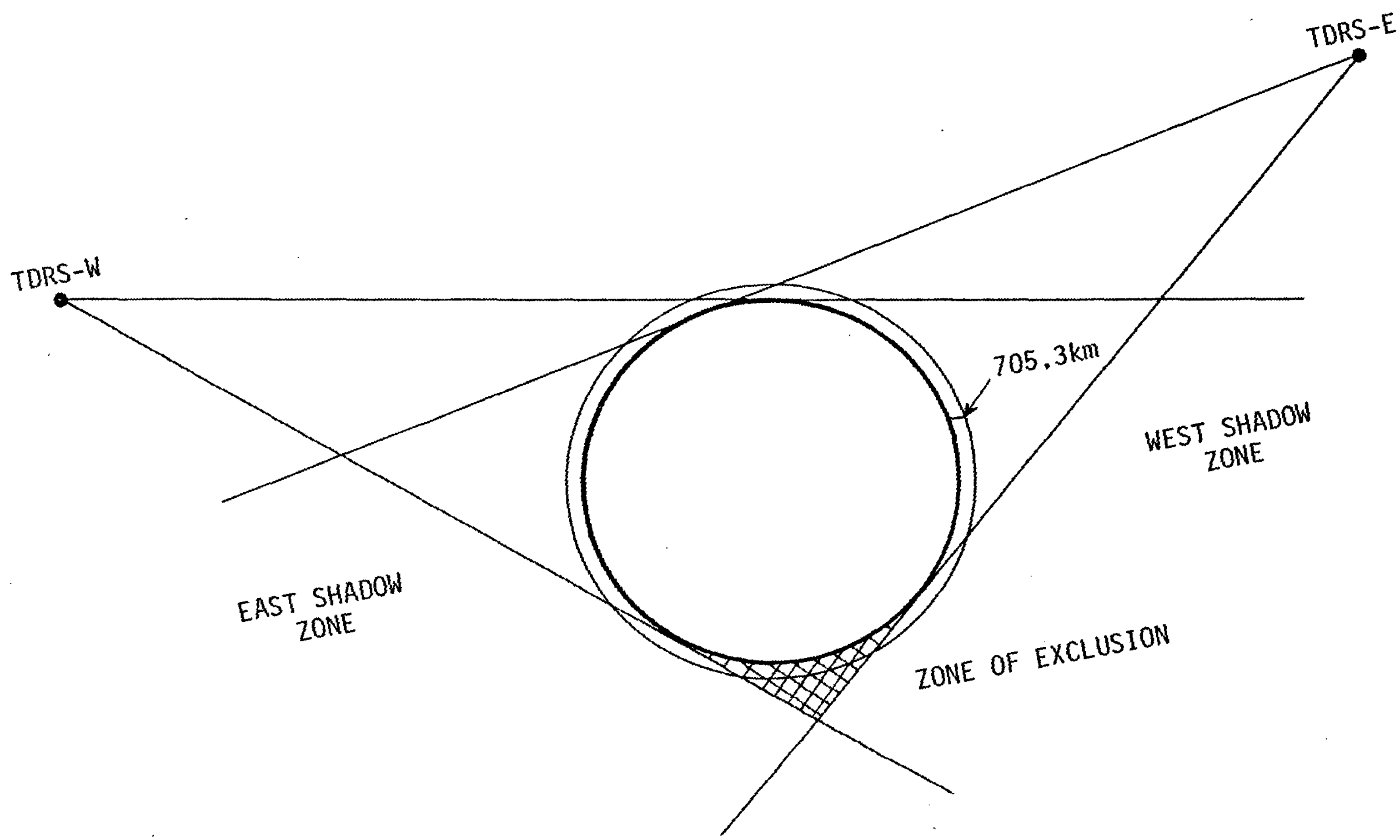


Figure 2-8. TDRSS Coverage Zone Geometry, Landsat D

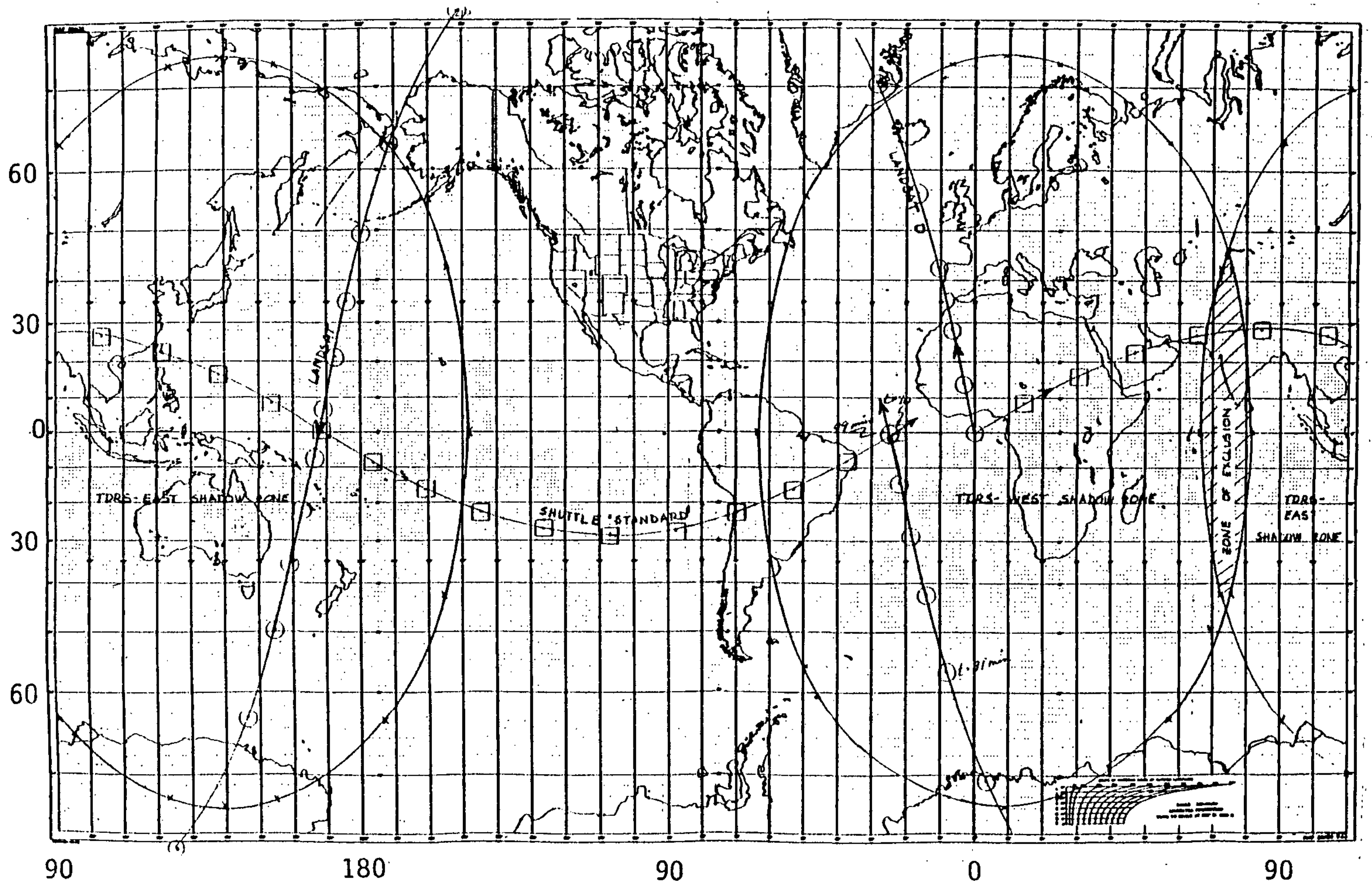


Figure 2-9. TDRSS Shadow Zones at Landsat D Altitude

can acquire data from the satellite, a limitation which reduces coverage of India, Sri Lanka, and other areas within a latitude band from 47.5°N to 47.5°S. Figure 2-9, which includes one orbit of the Landsat D ground track illustrates the conclusions discussed in the sections that follow.

2.3.1 LINK AVAILABILITY FOR ONE LANDSAT

At Landsat's altitude the TDRSS (two satellites) ZOE is a slit over latitudes $0 \pm 47.5^{\circ}$ and longitudes (at its widest point) 66.1°E to 81.9°E. Consequently, if Landsat remains without onboard storage capability and dependent on TDRSS alone for data transmission, there will never be any data retrieved for Sri Lanka and part of India. Of the possible 3270 minutes of science data in one Landsat cycle, 50 minutes or 1.5% cannot be retrieved due to the ZOE. Alternatives to overcome this limitation are discussed in Section 5.

In contrast to the ZOE, there is a large area where Landsat will be visible to both TDRSS satellites. This condition occurs when Landsat is over the North American continent, including Greenland and most of Alaska, as well as the western half on South America. Whenever Landsat is over these areas, it will have a choice of which TDRS to use.

During any one observation period, at least one TDRS is available (considering only geometry) to Landsat throughout the observation. In no case does geometrical availability require a switch from one TDRS to the other during an observation.

In conclusion, the Landsat satellite theoretically could establish a data relay link with either one or the other TDRSS 98.5% of the time the data observations require it. With only one TDRS available, Landsat has access to a data relay link 59% of the time. Finally, Landsat will not need to change data links in the middle of an observation, although a switch will be required when crossing the ZOE.

2.3.2 LINK AVAILABILITY FOR TWO LANDSATS

The Landsat mission may, at some time, include two satellites in identical orbits. Section 2.3.1 described the basic situation of a single Landsat

utilizing single access wideband TDRSS (KSA) services. Depending on the relative in-orbit spacing of the two Landsat satellites, this basic TDRSS availability may be available to both or be reduced because of interference. To illustrate the possibilities, two combinations of satellites were considered. The satellites are designated D and D' for convenience, although it is recognized that simultaneous operation of the initial members of the series is not presently planned.

Both combinations assume the satellites to be in identical, circular orbits with 9:45 a.m. descending nodes. These configurations are illustrated in Figure 2-10.

In the first combination, (configuration A, Figure 2-10) D' is seven days ahead of D in the 16-day repeat cycle, so the D' follows orbit path N+1 while D follows orbit path N. This provides global coverage in 8 days, while essentially giving observations 314 km wide, since the two observations will be temporally as well as spatially close.

In this combination, D' crosses the equator 1.5° west of D and is nominally 6.18 minutes behind D. However, this combination requires several instances of dual KSA coverage by TDRSS, since both satellites will be in view of the same TDRS, as well as observing simultaneously because of the proximity of their observation targets. For example, during a typical day of operation, D and D' together would transmit 450 minutes of data. Of that time, 120 minutes would require simultaneous KSA services. Of that 120, only 37 would occur while both TDRS are in sight of at least one Landsat. In other words, during a typical day of combined Landsat D and D' operation, 18% of their data might be lost, compared to the nominal loss of 1.5% (Section 2.3.1) if only one KSA link from each TDRS is available. As indicated above, if the two KSA links of each TDRS are available only the nominal loss of 1.5% due to the ZOE will accrue.

In the second combination, (configuration B) D' is eight days ahead of D in the repeat cycle, so the D' follows orbit path N+8, while D follows N. (Consecutive orbits follow path N+16.) Global coverage is complete in 8 days and because D' is nominally 49.44 minutes behind D, no instances of

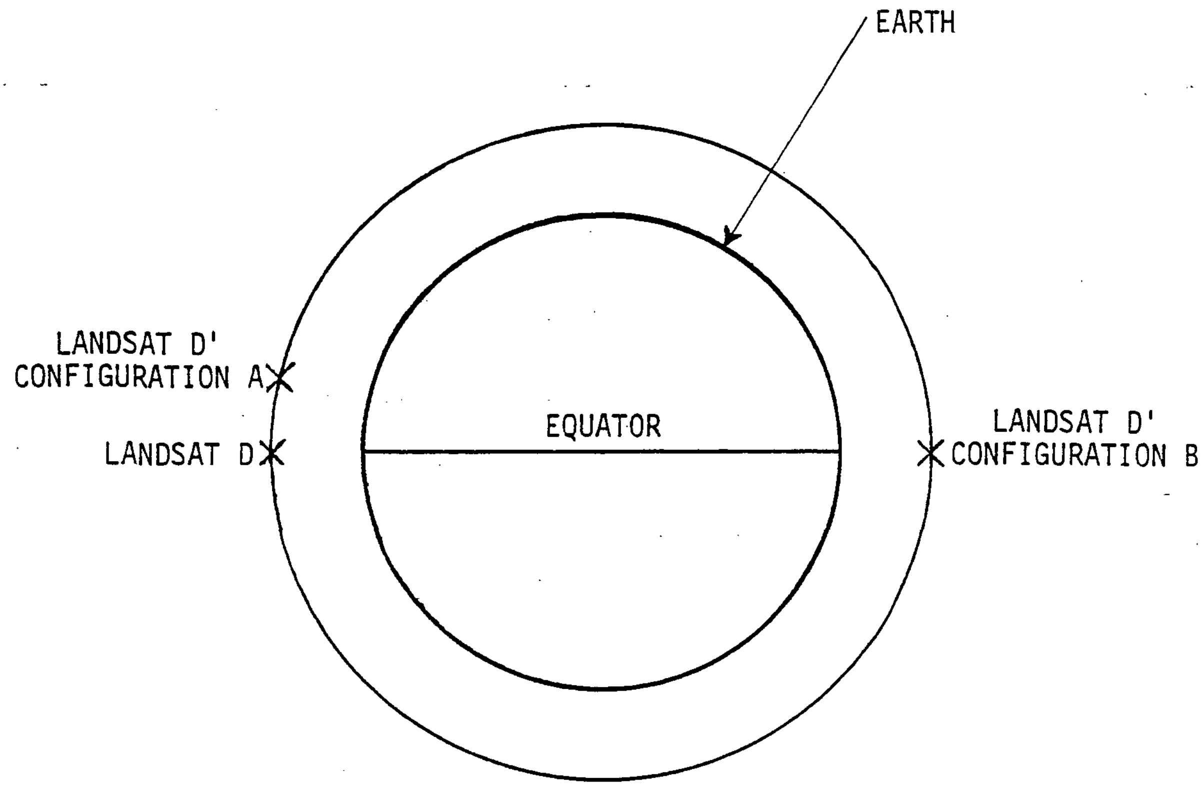


Figure 2-10. Landsat D and D' Configurations A and B. (Configuration A, D' is 7 days ahead of D; Configuration B, D' is 8 days ahead of D)

dual communications requirements arise. (This will remain true only as long as no or few night observations are taken.)

2.4 TDRSS LOADING REQUIREMENTS

The schedule of Landsat D observing opportunities developed as described in Section 2.2 provides a basis for a probable scenario for a Landsat transmission schedule. During the 16-day cycle 3270 opportunities were identified for observing land masses. They range in duration from less than ½ minute to 30 minutes. In translating the schedule of observing opportunities to a schedule of transmission requirements, the following assumptions were made:

1. Landsat will require the full transmission time possible.

2. Observing, and thus transmission, will not be interrupted for brief over-water intervals between more extensive land masses.

Under real operating conditions, the operating schedule may be reduced by various factors such as cloud forecasts, and data processing limitations, hence assumption 1 represents a maximum loading on TDRSS. Assumption 2 also recognizes that one and two minute gaps are too short for TDRSS to acquire a second user, service it, and re-acquire Landsat. For example, as the Landsat ground track crosses from Europe to Africa, for one minute it traverses the Mediterranean Sea. Where the observational schedule derived as in Section 2.2 shows two separate intervals, the transmission schedule shows one larger interval. The data are based on the 16-day set of maps described in Section 2.2, coupled with calculation of which TDRS (East, West, or both) was visible for each interval. Two methods were used; one employed a global map with the shadow zones marked (as in Figure 2-9), the other used the computer program (Appendices A, B and C) which in addition to calculating Landsat's position also determines TDRSS visibility for each point.

2.4.1 TRANSMISSION INTERVALS

An example of the analysis of one of the 16 days studied is shown in graphical form in Figure 2-11. During this period 21 separate transmission

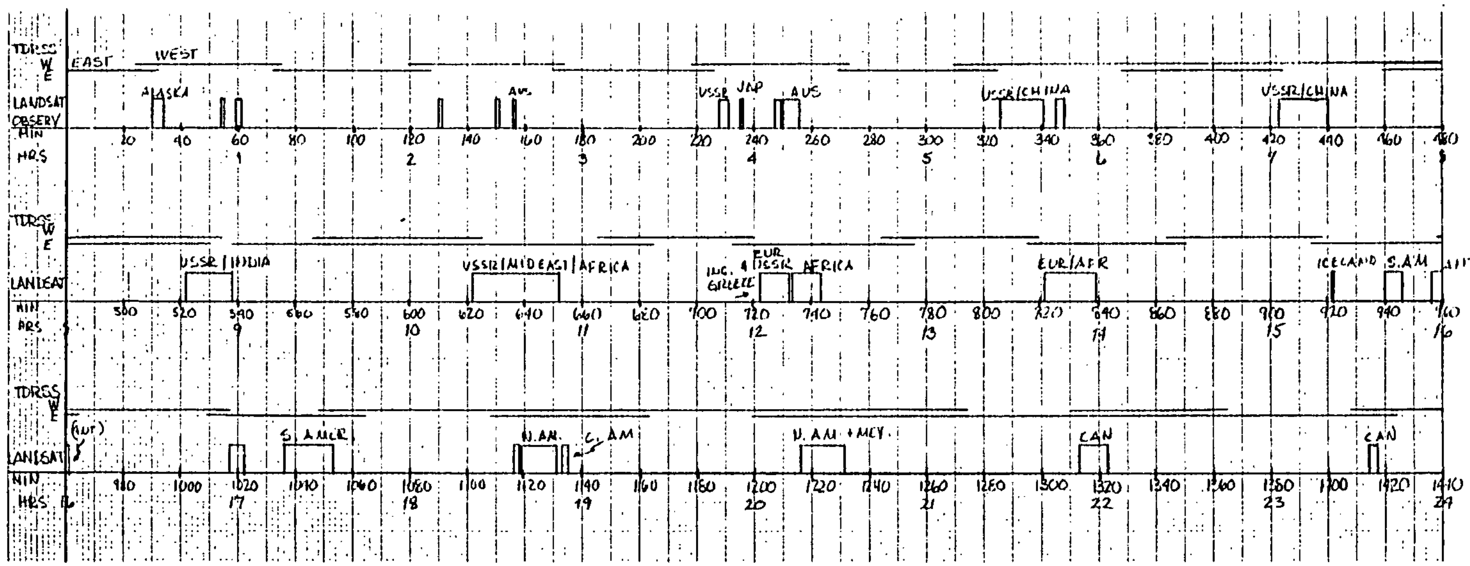


Figure 2-11. TDRSS Visibility and Landsat Observation Schedule Pattern for One Day of the 16-day repeat cycle

Table 2-4. Transmission Intervals Statistics

Interval Length (Minutes)	EAST ONLY # Intervals	EAST ONLY # Transmission data minutes	WEST ONLY # Intervals	WEST ONLY # Transmission data minutes	BOTH # Intervals	BOTH # Transmission data minutes	TOTAL # Intervals	TOTAL # Transmission data minutes
1/2	5	3	11	5	2	1	18	9
1	18	18	19	19	12	12	49	49
2	2	4	19	38	12	24	33	66
3	5	15	10	30	17	51	32	96
4	5	20	8	32	18	72	31	124
5	1	5	9	45	7	35	17	85
6	3	18	8	48	6	36	17	102
7	-	0	4	28	3	21	7	49
8	5	40	4	32	8	64	17	136
9	3	27	5	45	3	27	11	99
10	2	20	7	70	5	50	14	140
11	1	11	6	66	4	44	11	121
12	1	12	6	72	2	24	9	108
13	2	26	1	13	6	78	9	117
14	4	56	6	84	4	56	14	196
15	2	30	2	30	8	120	12	180
16	5	80	5	80	7	112	17	272
17	9	153	6	102	2	34	17	289
18	8	144	2	36	1	18	11	198
19	6	114	1	19	1	19	8	152
20	4	80	2	40	-	0	6	120
21	2	42	6	126	-	0	8	168
22	-	0	2	44	-	0	2	44
23	1	23	-	0	-	0	1	23
24	2	48	-	0	-	0	2	48
25	1	25	-	0	-	0	1	25
26	-	0	-	0	-	0	-	0
27	1	27	-	0	-	0	1	27
28	3	84	-	0	-	0	3	84
29	5	145	-	0	-	0	5	145
30	3	90	-	0	-	0	3	90
TOTALS	111	1360	149	1104	128	898	386	3362
Percentage of Total Transmission Time Required	40.4%		32.8%		26.7%			
Average Interval Length = 12.25			7.41		7.02		8.71 = 14.6%	
Average per day = 85			69		56		210	

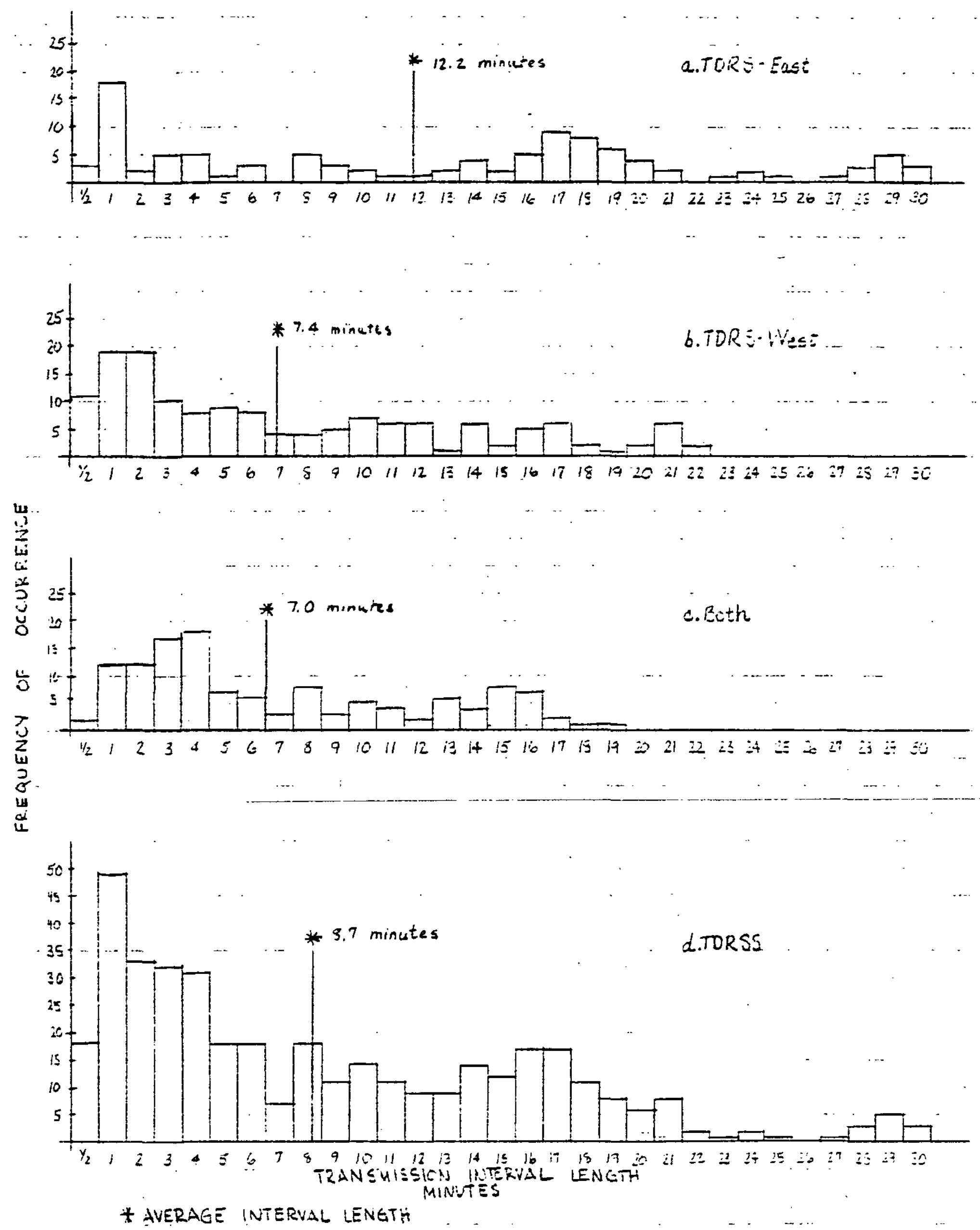


Figure 2-12. Histograms illustrating frequency of data transmission requirements during 1 cycle as a function of interval length of transmission for (a) TDRS-E; (b) TDRS-W; (c) TDRS-E and TDRS-W; (d) TDRSS

intervals occur. The analysis included a determination of whether the transmission requirement was on TDRS-E only, or TDRS-W only. Also identified were cases in which transmission could be to either the E or the W relay and the number and duration of intervals which could be met by the full TDRS (2-satellite) system. The results of the analysis are given as freqency distributions in Table 2-4, and in histogram form in Figure 2-12. Transmission to TDRS-E only will be required for 1360 minutes, to TDRS-W only for 1104 minutes; for a total of 898 minutes transmission can be to either TDRS, giving a grand total of 3362 minutes distributed over 16 days, for an average of 210 minutes/day, or 14.4 minutes per orbit.

For the total system, the analysis shows that the 476 observation intervals covering a total of 3280 minutes of the 16-day cycle have been reduced to 386 TDRSS transmission intervals requiring a total of 3362 minutes or 14.6 percent of the 23040 minutes in the 16-day repeat cycle. The average length of the 386 transmissions is 8.7 minutes, but 26 of them would be over 20 minutes, as compared to 16 observation intervals which exceed 20 minutes.

2.4.2 TDRS-EAST

From Table 2-4 and from comparison of the four histograms of Figure 2-12 it can be seen that, on the basis of transmission time, Landsat will rely more heavily on TDRS-E than on TDRS-W. A total of 1360 minutes, or 40% of Landsat's data can be transmitted only through TDRS-E, compared with 33% for TDRS-W alone and 27% for either. If the 27% is divided equally between the two, TDRS-E will transmit 54% of Landsat's data.

The global map in Figure 2-9 clearly shows why the two TDRS's are unequally loaded. In the TDRS-E coverage zone are mostly large land masses, particular Europe and Africa, as well as the Americas and a large area of Western Asia and the Middle East. In contrast TDRS-W covers the Pacific Ocean where Landsat is not scheduled to take much data.

The multi-modal frequency distribution on the TDRS-E histogram (Figure 2-12a) reflects the three large land masses of the East-only coverage zone: South America, Europe/Africa, Western Asia and the Middle East.

Europe and Africa are noted as one large land mass, contrary to the customary Eurasia, because Landsat's north-south ground track covers Europe and Africa, rather than Europe and Asia in one orbit path. The 24-minute and longer transmission intervals are due solely to the Europe/Africa observations.

The peak at the one- and two-minute length transmission intervals is a persistent feature in all four charts of Figure 2-12 because of islands and peninsular land areas.

2.4.3 TDRS-WEST

As noted above, Landsat D will require TDRS-W less often than TDRS-E because the West coverage zone includes the Pacific ocean. As a corollary, the one- and two-minute peak of Figure 2-12b is particularly strong because of the abundance of islands rather than continents, in the West coverage zone. These include Hawaii, the South Sea Islands, New Zealand, Indonesia, the Phillippines, the Southeast Asian Archipelago and Japan. Continents included in the West coverage are Australia and the eastern portion of Asia.

2.4.4 DOUBLE TDRS COVERAGE

When Landsat D is near the poles, North and Central America, or parts of South America, it will be visible to either TDRS. The peaks in the double coverage histogram relate to cross-continental coverage (about 15 minutes) and peninsular, or otherwise projecting continental areas such as Alaska and northern South America (about 4 minutes).

2.4.5 TOTAL SYSTEM (TDRSS) REQUIREMENTS

In combining the requirements of the three types of coverage zones, TDRSS will be needed by Landsat D for science data transmission for an average of 210 minutes per day, or almost 15% of the capability of one of the four links. However, Landsat does not remain continuously in view of one TDRS, but for four or five orbits is in the West coverage zone, then in the East zone, etc. Consequently, the 15% requirement may be divided between the two TDRS's; Landsat will require TDRS-E 7.8% of its time, and TDRS-W 6.7%. In other words, of the 1440 minutes of every day that TDRS-E can relay

data, 113 minutes will be scheduled for Landsat, on the average. Likewise, TDRS-W will be scheduled for Landsat for an average total per day of 97 minutes. These results are illustrated in the pie chart of Figure 2-13.

Of the 233 orbits of one cycle period, three will require no TDRSS wide-band transmission support. Each of the remaining 230 could require some transmission, but this support will be needed only during the daylit portion of the orbit. In some instances, it will be needed for as much as 30 minutes; in other orbits it will be needed for up to 5 intervals distributed, (as illustrated in Figure 2-11) throughout the daylit orbit. These periods of transmission activity are separated by longer intervals of at least 69 minutes when TDRSS support is not required.

If two Landsats are in orbit in a non-interference configuration, the percentage of required TDRSS time doubles to 15% of TDRS-E and 14% of TDRS-W. Thirty-minute active intervals for each satellite will be interspersed with 19 minutes of no Landsat activity. Of course, as mentioned above, those thirty minutes intervals are very seldom blocked completely to any other user, since each Landsat on the average requires only 15 minutes of each active interval. Half-day timelines illustrating these active/inactive intervals of Landsat transmission are included as Figure 2-14.

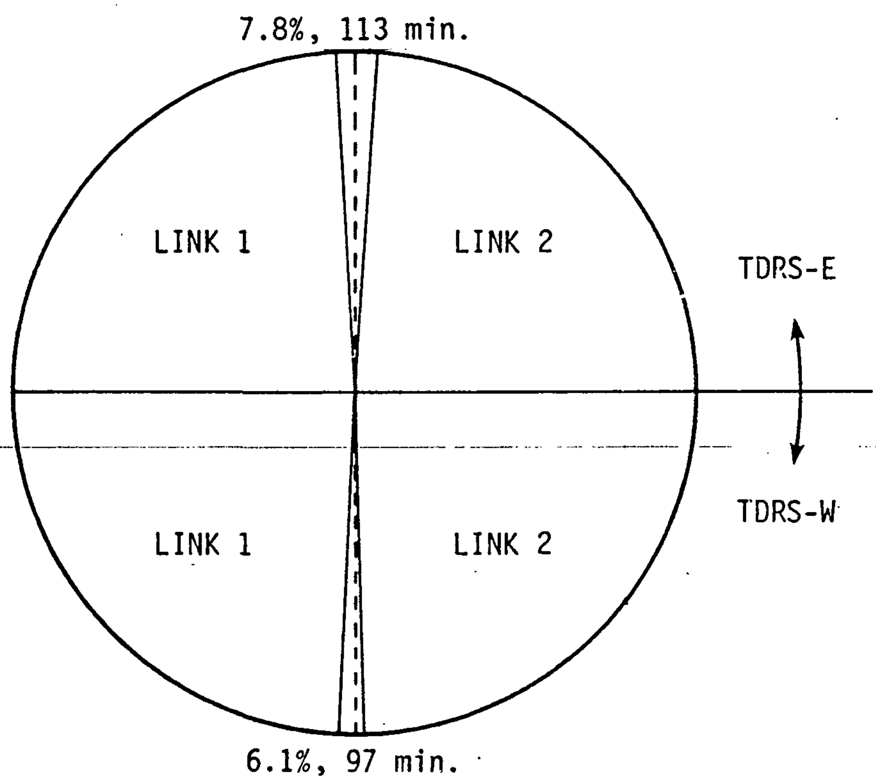


Figure 2-13. Landsat D Loading Requirements on TDRSS

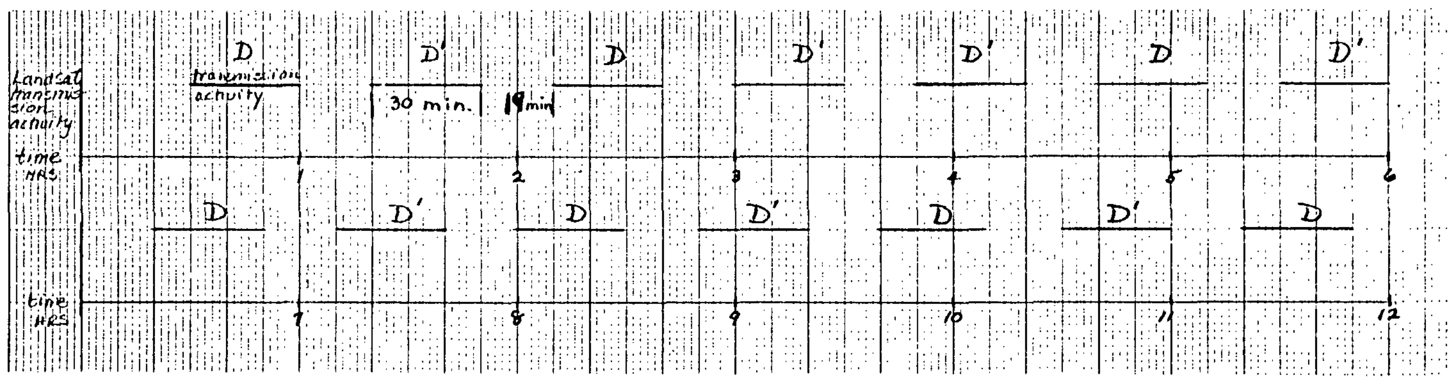


Figure 2-14. Composite Landsat D and D' Active Transmission Intervals Over a 12-hour Period

SECTION 3. TELECOMMUNICATIONS REQUIREMENTS OF NON-LANDSAT USERS

Because the TDRSS will serve the telecommunications and tracking requirements of all NASA spacecraft, Landsat may reasonably expect pre-emption of link availability, and consequent loss of data, by other spacecraft. To determine how much of data loss might be expected, the telecommunications requirements of other missions, primarily resource observation missions, were examined; their potential impact on Landsat data retrieval is examined in Section 4.

Except for the Space Transportation System (Shuttle), no other mission of the 1985-1989 time frame had requirements of such a nature as to produce a more than negligible impact on Landsat D. In particular, a KSA link (wideband service) was not required by any mission, other than Shuttle. Even the Space Telescope has a requirement only for narrow-band SSA link services at 1.024 Mbps. Thus only Shuttle gives Landsat any competition for the wideband link. Consequently the telecommunications requirements of the Shuttle missions were examined in some detail.

Using the NASA list of scheduled Shuttle launches, eleven types of Shuttle orbits were identified. They are listed in Table 3-1 grouped by inclination, orbital altitude and flight duration. Because of the similarity in these orbits only three were chosen for analysis (Table 3-1). Of these, two have the same altitude, but different inclinations, while two have the same inclination, but different altitudes.

The labels of "Standard", "Spacelab", and "Space Telescope" were assigned for convenience, and merely reflect the type of missions most likely to use the orbits.

3.1 DETERMINATION OF TELECOMMUNICATIONS REQUIREMENTS

The Shuttle will use TDRSS to maintain complete and continual communications between its crew and Shuttle's Mission Control. The problem of determining the telecommunications requirements is again one of simple

Table 3-1. Representative List of Typical Shuttle Orbits

MISSION TYPE	INCL. (deg.)	HEIGHT (nm)	DURATION (days)
"STANDARD"	28.5	160	7
	28.5	150	2
	57.0	135	7
"SPACELAB"	57.0	160	7
	57.0	200	7
	28.5	272	5
	28.5	240	5
"SPACE TELESCOPE"	28.5	320	3
	28.5	99	7
	50	202	5
	46.9	160	5

geometric visibility: whenever TDRSS can see the Shuttle, one wideband data relay link (KSA) is required.

The geometric visibilty of Shuttle to TDRSS was determined as a function of time and Shuttle's position in its orbit. The same computer program as used for Landsat was employed here, with the appropriate changes in input data (spacecraft altitude, inclination, and period).

The results of the program confirmed the graph in Figure 3-1 and prompted the following comments on Shuttle/TDRSS link availability:

- The amount of geometric coverage (availability) is a function of Shuttle orbital altitude and inclination.

- At low altitudes and low orbital inclinations, Shuttle passes horizontally through the geometric ZOE at its widest points and on every orbit, receiving the least coverage.

- At high orbital inclinations, Shuttle passes through the geometric ZOE only periodically but follows the length, rather than the width, of the slit-shaped ZOE. Therefore, each passage will be for a longer length of time, but total coverage is greater than at lower inclinations.

3.2 LOADING REQUIREMENTS OF THE SHUTTLE MISSION

The loading requirements of the three representative Shuttle missions are tabulated in Table 3-2, since for Shuttle, link availability is tantamount to load requirement. Although, for some Shuttle attitudes, its Ku-band antenna is obscured and TDRSS communication interrupted, this factor was ignored in preparing Table 3-2, since Shuttle attitudes cannot be specifed at the present time.

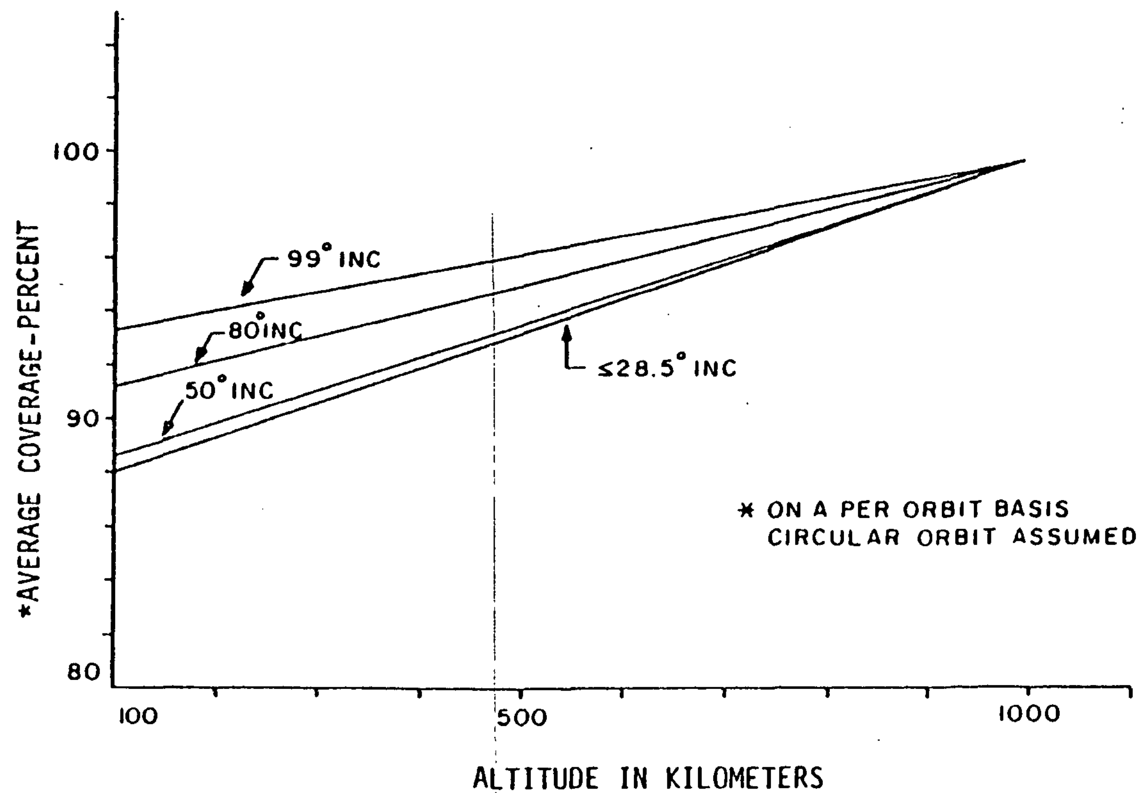


Figure 3-1. Average Geometric Coverage Versus User Altitude, Various Inclinations

TABLE 3-2. STS/TDRSS LINK AVAILABILITY

Type of STS Mission	Single TDRS Communication Availability		Period of Obscuration		Dual Availability		Availability Per Orbit	
	Minutes	%	Minutes	%	Minutes	%	Minutes	%
"STANDARD" I-28.5^{0} H-160nmi	45-50	50-55	5-15	5.5-16.7	9-14	10-15	80.5	89
"SPACELAB" I-57^{0} H-160nmi	45-54	50-60	5-18	5.5-20	4-22	4.4-24	80.5	89
"SPACE TELESCOPE" I-28.5^{0} H-320nmi	53-58	58-64	5-10	5.5-11	14-20	14.5-21	89	92

SECTION 4. COMPOSITE LANDSAT AND OTHER RESOURCE OBSERVATION SPACECRAFT TELECOMMUNICATION REQUIREMENTS FOR TDRSS SERVICE

The impact of other spacecraft on Landsat D data retrieval can be determined from a composite schedule of requirements for TDRSS service. A composite schedule which combines on the same timeline the estimated telecommunications requirments schedule for each spacecraft provides a probable scenario of how the Landsat link availability may be affected by other demands for TDRSS services.

Several resource observation missions were examined for possible inclusion in the composite schedule but, as noted in Section 3, only the Space Transportation System (Shuttle) competes significantly with Landsat D for the KSA links. Therefore, only the loading requirements of Landsat and Shuttle were determined and used in the preparation of the composite schedule.

4.1 CORRELATION OF LANDSAT-SHUTTLE TELECOMMUNICATION LINK DEMANDS

Correlation of the two loading schedules was accomplished by overlaying the schedules on their independent variable, time. Because the initial conditions of these two schedules were unknown and difficult to estimate and moreover, because a real temporal relationship between the two is impossible to guess prior to actual launch, arbitrary conditions were chosen and the two schedules related in a series of equally arbitrary combinations. The resulting correlation of link demands is actually a series of samples 24 hours long. Durations of time intervals where simultaneous demands could possibly exist were determined and summed to give the amount of time Landsat and Shuttle both require KSA links from the same TDRS spacecraft. These values were averaged to give the correlation results: estimates of conflicting link demands, i.e., estimates of Landsat's possible data loss.

Additional results of the correlation are geographical. Besides data loss estimates, the analysis provided knowledge of which geographical areas are most and least likely to be affected by link priority demands.

The results of the correlation analysis are described in detail in Section 4.2. A more complete description of the study's methodology, including the assumptions made, is continued in this section.

4.1.1 ASSUMPTIONS

The correlation analysis was based on the following set of assumptions:

- Data loss estimates are based on worst case, i.e., that both Shuttle and Landsat will need the same link (KSA).
- Shuttle has priority on TDRSS over Landsat.
- Shuttle will pre-empt only one KSA link at a time.
- If both TDRS are available to Shuttle, it may switch links to accommodate Landsat.
- Landsat will transfer its link from one TDRS to the other during an observation (i.e., over a land mass).
- Switching TDRSS from Shuttle to Landsat, and vice versa, takes approximately two minutes.

4.1.2 SAMPLING METHODOLOGY

The correlation of the Landsat and Shuttle link availability schedules was basically a simple geometric visibility comparison as a function of time, complicated only by the inclusion of the estimated Landsat observation schedule Appendix D. Because of the uncertain relationship between the two schedules, they were combined in various ways, as described below, each combination providing one sample of the correlation analysis.

The baseline sample was made by giving the Landsat and Shuttle schedules identical initial conditions, for t_0; ϕ and θ (ϕ = latitude, θ = longitude). Additional samples were made by varying the relationship between t_0, which since ϕ and θ depend on t, consequently varied the relationship between all the initial conditions. These additional samples measured the sensitivity to the uncertainty between schedules.

The baseline comparison consisted of three 1-day samples of the same temporal relationship, which was $t_0 = \phi = \theta = 0$ for both Landsat and Shuttle. The first sample consisted of the interval $t = 0$ to $t = 24$ hours,

the second t = 72 to t = 96 hours, the third t = 120 to t = 144 hours, i.e., the first, fourth, and sixth (shuttle) days. The purpose of this was to determine the consistency of the interference between the missions during the typical Shuttle mission duration of seven days.

The additional samples varied t_0 of the Shuttle as a function of time in the first Landsat orbit and day in the Landsat 16-day cycle. Also varied was θ_0, or the longitude of the beginning orbit. This sampling procedure provided up to 16 samples.

An example of one of these samples is included as Figure 4-1. It is a timeline on which are noted Landsat observation intervals, Landsat's geometric visibility with TDRS-E and TDRS-W, and Shuttle's visibility with TDRSS.

4.2 RESULTS OF CORRELATION ANALYSIS

From each sample, such as Figure 4-1, are added for one day the total potential data acquisition time in minutes of Landsat data, the number of minutes when Landsat and Shuttle are visible to the same TDRS and only that TDRS, and the number of minutes of Landsat observation time with uncontested link availability. The first item is clearly the sum of the other two. For each sample, the three sums were determined and used to calculate a percentage of possible Landsat data loss. The percentages varied without a clearly recognizable pattern, and so give only the maximum, minimum and average data loss that can be expected.

The results for the three types of Shuttle orbits are listed in Table 4-1. Again, these are worst case results, when both Landsat and Shuttle have access to only one KSA link per TDRS. With all four KSA links in operation, Landsat may expect only a very small impact by the Shuttle on data retrieval. Data losses apply only for the duration of a Shuttle flight, and considered on an annual basis will be very small.

The variation from day to day in the amount of pre-empted data transmission appears to be caused by the difference in the orbit characteristics, mainly in the orbital periods. They are completely independent (90.45 minutes for the standard Shuttle, 98.88 for Landsat) and cause the orbits never to remain close together in time and space for very long.

Day "1" Cycle Beginning, STS = 57° Inclination "SPACELAB ORBIT"

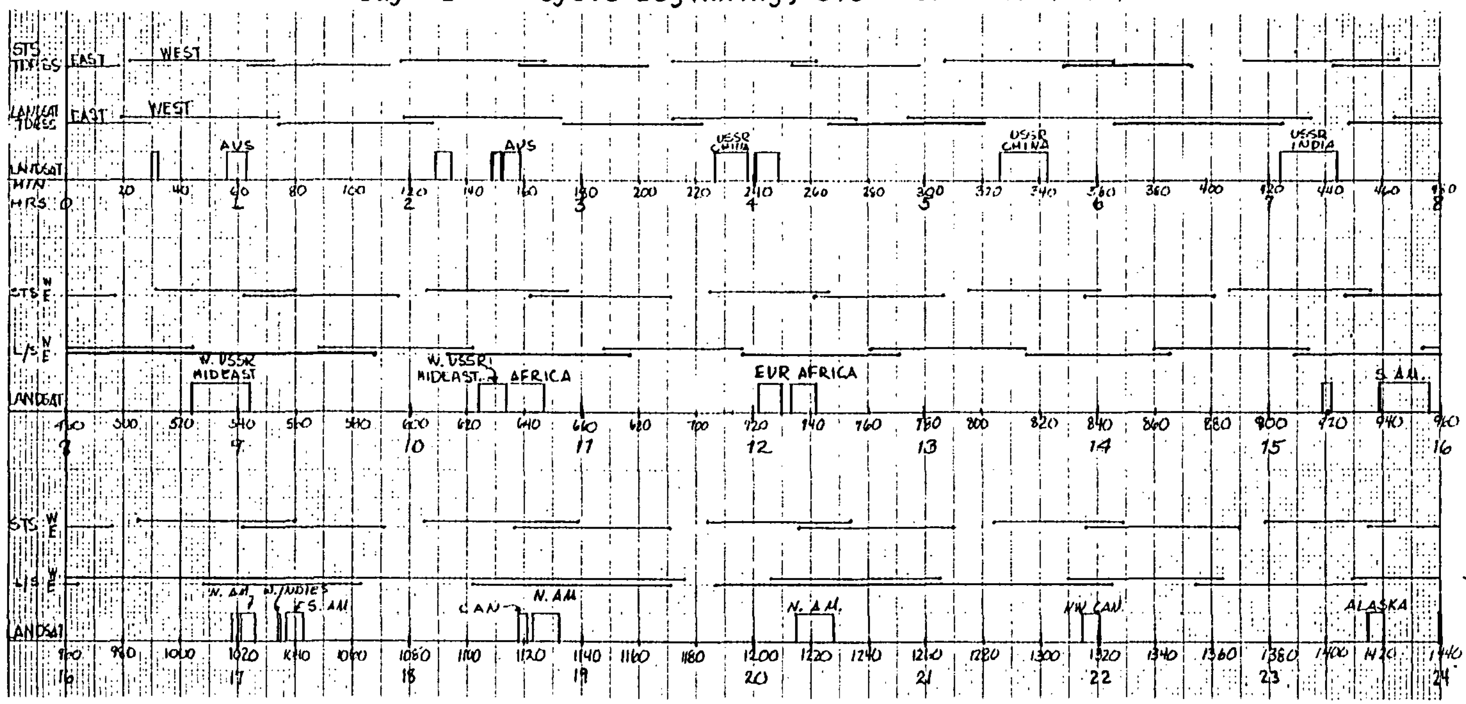


Figure 4-1. Sample of Superimposed Timelines of Landsat D TDRSS Availability Landsat D Observation Schedule, and Shuttle TDRSS Availability

Table 4-1. Correlation Results

SHUTTLE ORBIT TYPE	Landsat D Communication Time Pre-empted by Shuttle		
	MAXIMUM (PERCENT)	MINIMUM (PERCENT)	AVERAGE (PERCENT)
"STANDARD" 28.5^{o}m 160nmi	41	10	28
"SPACELAB" 57^{o}, 160nmi	43	6	28
"SPACE TELESCOPE" 28.5^{o}, 320nmi	48	7.5	31

In the 1985-1989 time frame the Shuttle will be up considerably less than half time (3 to 7 day mission duration with most missions only 3 days and a maximum of 24 flights per year). Only during those times when the Shuttle is up will there be a potential of continuous pre-emption of one TDRSS link.

The geographic areas subject to possible loss of data by pre-emption of the KSA link are those areas covered by only one TDRSS link. Consequently, it will always be possible to observe Alaska and the coterminous United States with Landsat via TDRSS. Observation of other large areas of interest, such as Europe, Africa, Australia, etc., could be cut as much as 40% or 50%. No area is ever completely blocked for a full seven-day Shuttle mission, even with only one KSA link per TDRS.

SECTION 5. TELECOMMUNICATIONS ALTERNATIVES FOR LANDSAT MISSIONS UTILIZATION OF TDRSS.

5.1 LANDSAT TELECOMMUNICATIONS SYSTEM

Before telecommunications alternative to Landsat D are considered, it is advantageous to review those facilities which will be available on board the spacecraft and on the ground during the 1985 time frame and beyond.

The communications system of the Landsat D series between the spacecraft and the ground are being provided by RF link services to either one or various combinations of the Ground Spaceflight Tracking and Data Network (GSTDN), a Transportable Ground Station (TGS), foreign owned ground stations, or the TDRS ground terminal at White Sands, N.M.

A wideband communications subsystem will provide the Landsat D spacecraft with the capabilities for transmitting Multispectral Scanner (MSS) and Thematic Mapper (TM) instrument data to both TDRSS and other ground based users. When operating in the TDRSS mode, Landsat D utilizes the capability for acquiring and tracking TDRS forward link transmission at K-band frequencies.

The flight segment of Landsat's telecommunications system supports, (1) RF links to transmit images of TM and MSS instruments to the ground by means of TDRSS, (2) telemetry channels for monitoring of vital flight segment functions and (3) command capabilities to control flight segment operation from the ground. The flight segment interfaces with the Data Management System (DMS) on the ground through:

a. A Domsat link from White Sands, N.M. where the flight segment data are recorded and forwarded after being relayed by TDRSS from space to ground.

b. A Transportable Ground Station (TGS) located at GSFC which receives instrument data (telemetry, TM and MSS images).

c. The Ground Spaceflight Tracking and Data Network (GSTDN) stations located at Goldstone and Alaska will play back recorded data through a DOMSAT link to GSFC.

The control side of the flight segment interfaces with the Operations Control Center (OCC) through the reception of telemetry and generation/transmission of commands by means of RF S-band transmissions through TDRSS and GSTDN.

The Landsat flight segment is also equipped to transmit to foreign (non-NASA) users, who could receive direct RF transmissions at X-band of TM and MSS data, and at S-band for MSS only.

The above information indicates that the Landsat telecommunication flight segment is configured to provide communication services with or without operational TDRSS.

5.1.1 LANDSAT D DATA FLOW WITHOUT OPERATIONAL TDRSS

Since Landsat D will be launched before TDRSS is operational, direct communications to the ground are provided in conformance with the telecommunications plan shown in Table 5-1, which assures the data flow illustrated in figure 5-1. In this configuration, the spacecraft uses a NASA standard transponder (5-watt option) for command, telemetry and ranging communications with GSTDN and for telemetry transmission to direct readout ground stations through an omni antenna. The S-band downlink frequency is 2287.5 MHz and the uplink (Earth to Landsat) frequency is 2016.4 MHz. The GSTDN telemetry format consists of 8 kbps BiØ (IRIG) real time telemetry, sometimes in combination with either STDN ranging or 32 kbps telemetry. This downlink is also used for BiØ (IRIG) computer dumps of payload corrective data (PCD) or 256 kbps BiØ (IRIG) NBTR data. The GSTDN command data rate on the uplink is 2 kbps NRZ-M in addition to the ranging data at standard rates.

Landsat D MSS data can be transmitted to direct readout ground stations (ULA, GDS, TGS, and foreign ground stations) at S-band (2265.5 MHz). Both MSS and TM sensor data can also be transmitted to the transportable ground station (TGS) and foreign (non-NASA) ground stations over an X-band link (8212.5 MHz).

The direct readout S-band equipment on the spacecraft consists of a 10 watt PCM/FM transmitter driving an Earth oriented shaped beam antenna for transmission of 15.0626 Mbps NRZ-L MSS sensor (image) data. The direct

Table 5-1. Landsat D Telecommunications Plan (Without Operational TDRSS)

- DOWNLINKS - LANDSAT TO EARTH

  1 FOREIGN STATIONS
  2 TRANSPORTABLE GROUND STATION (TGS)
  3 UNIVERSITY OF ALASKA (ULA)
  4 GOLDSTONE (GLD)
  5 GSTDN

FREQUENCY (S-Band) 2287.5MHz	REAL TIME TELEMETRY (TLM	1 5
	PAYLOAD CORRECTION DATA	1 5
	NARROW BAND TAPE RECORDER DATA (NTBR)	5
	ON BOARD COMPUTER DATA	5
FREQUENCY (S-Band) 2265.5MHz	MULTI-SPECTRAL SENSOR DATA DATA (MSS)	1 2 3 4
Frequency (X-Band) 8212.5MHz	TM and/or MSS	2 1

- UPLINK GSTDN TO LANDSAT

FREQUENCY (S-Band) 2106.4 MHz	COMMAND (CMD), RANGING

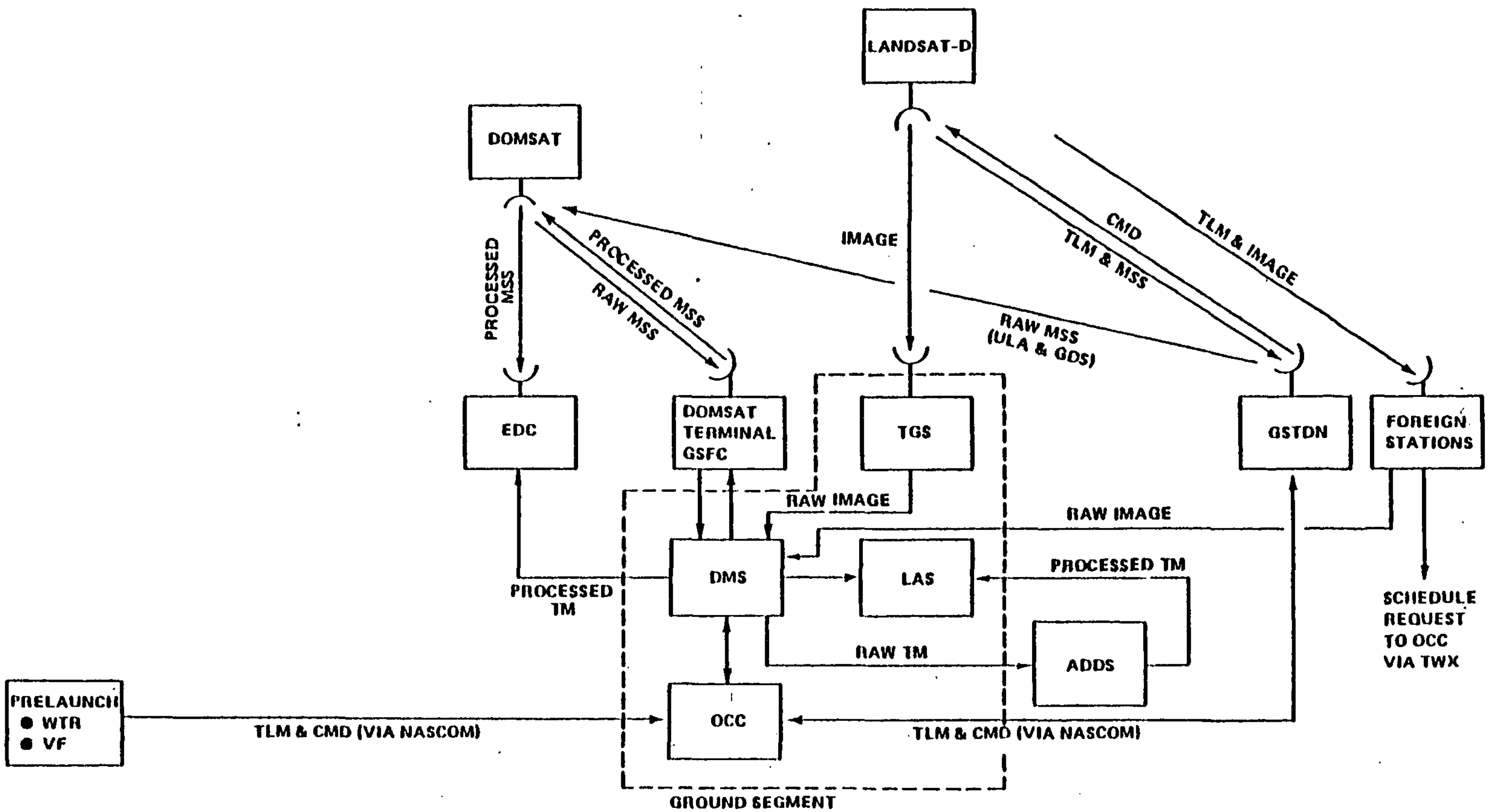


Figure 5-1. Landsat Overall Data Flow (Without Operational TDRSS)

readout X-band spacecraft equipment consists of a 42 watt unbalanced quadra-phase-shift-keyed (UQPSK) transmitter and an Earth-oriented shaped beam antenna for transmitting either 15.0626 Mbps NRZ-M MSS image data and/or 84.903 Mbps NRZ-M TM sensor data. A PN code is substituted for the TM data when only MSS data is transmitted.

All command, telemetry and wideband data handling equipment is redundant except for antennas, and transponder transmitters. The transponder transmitters are redundant for non-simultaneous communications.

5.1.2 LANDSAT D DATA FLOW WITH OPERATIONAL TDRSS

The Landsat D communications plan (with operational TDRSS) is summarized in Table 5.2 and the data flow is illustrated in Figure 5-2. Landsat D uses the NASA standard TDRSS 5 watt option transponder for command, telemetry and ranging communications with the TDRS spacecraft. The Landsat D high-gain, mechanically steered antenna (Figure 5-3) is equipped with S-band and Ku-band feeds which communicate with the TDRS multiple access (MA) antenna for normal communications (125 cps command, 8 kbps real time telemetry) and TDRSS ranging. The 1.8 meter steerable SSA antenna for high-rate communications (1.0 kbps, 8.0 kbps real-time, TDRSS ranging, and 32.0 kbps computer dump or PCD data on 128 kbps MBTR data) will be part of the TDRSS services. The omni-antenna communicates with the TDRSS S-band single access (SSA) antenna for launch support and backup communications (125 bps command and 1.0 kbps real-time telemtry and TDRSS ranging). The 1.0; 8.0; 32.0 and 128.0 Kbps telemetry signals are nonreturn to zero NRZ-M convolutionally encoded and transmitted by the TDRSS coded spread spectrum system. Simultaneous communications with TDRSS and GSTDN will be available. TDRSS S-band forward and return link frequencies are the same as those used by the GSTDN uplink (2106.4 MHz) and downlink (2287.5 MHz).

Landsat D MSS and TM sensor data can be transmitted at Ku-band via the TDRS single access (KSA) return link (15003.4 MHz). The spacecraft Ku-band equipment consists of a mechanically steerable 1.8. meter paraboloidal antenna, a 22 watt UQPSK Ku-band transmitter, and an autotrack receiver that operates on the 13.775 MHz TDRS forward link. Autotrack is the normal mode of antenna steering for Ku-band operation. Program tracking using instructions from an onboard computer, is used for acquisition and backup.

Table 5-2. Landsat D Telecommunications Plan (With TDRSS Operational)

- DOWNLINKS - LANDSAT TO TDRSS GROUND TERMINAL (WHITE SANDS N.M.)

	1.8 M ANTENNA POINTS TO TDRS EAST	
	1.8 M ANTENNA POINTS TO TDRS WEST	
FREQUENCY (S-BAND) 2287.5 MHZ	MA REAL TIME TLM	SQPSK PN SPREAD
	MA RANGING	SQPSK PN SPREAD
	SSA REAL TIME TLM	SQPSK PN SPREAD
	SSA OBC OR PCD	SQPSK PN SPREAD
	SSA NTBR DATA	SQPSK PN SPREAD
	SSA RANGING	SQPSK PN SPREAD
FREQUENCY (KU-BAND) 15003.4 MHZ	KSA TM IMAGE DATA	UQPSK (84.903 Mbps)
	KSA MSS IMAGE DATA	UQPSK (15.0626 Mbps)

- UPLINKS - TDRSS GROUND TERMINAL TO LANDSAT VIA TDRS-E AND TDRS-W

FREQUENCY (S-BAND) 2106.4 MHZ	MA LOW RATE COMMAND	SQPSK PN SPREAD
	MA RANGING	SQPSK PN SPREAD
	SSA COMMAND	SQPSK PN SPREAD
	SSA RANGING	SQPSK PN SPREAD
	SSA BACK UP COMMAND	SQPSK PN SPREAD
	SSA RANGING COMMAND	SQPSK PN SPREAD
FREQUENCY (KU-BAND) 13775 MHZ	KSA KU-BAND AUTO TRACK	SQPSK PN SPREAD

SQPSK STAGGERED QUADRIPHASE SHIFT KEYED
UQPSK UNBANDED QUADRIPHASE SHIFT KEYED
PN PSEUDONOISE

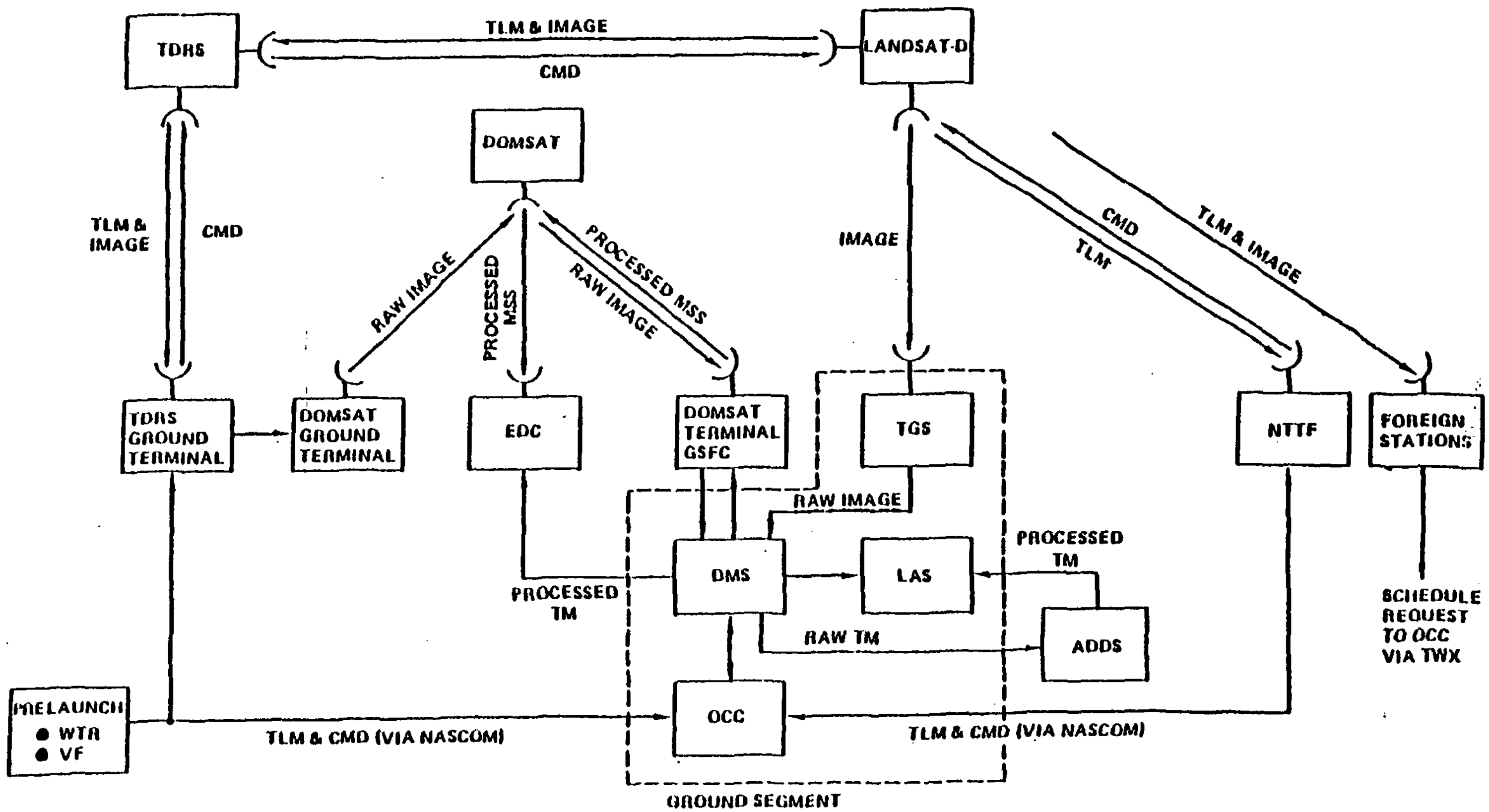


Figure 5-2. Landsat D Overall Data Flow (With Operational TDRSS)

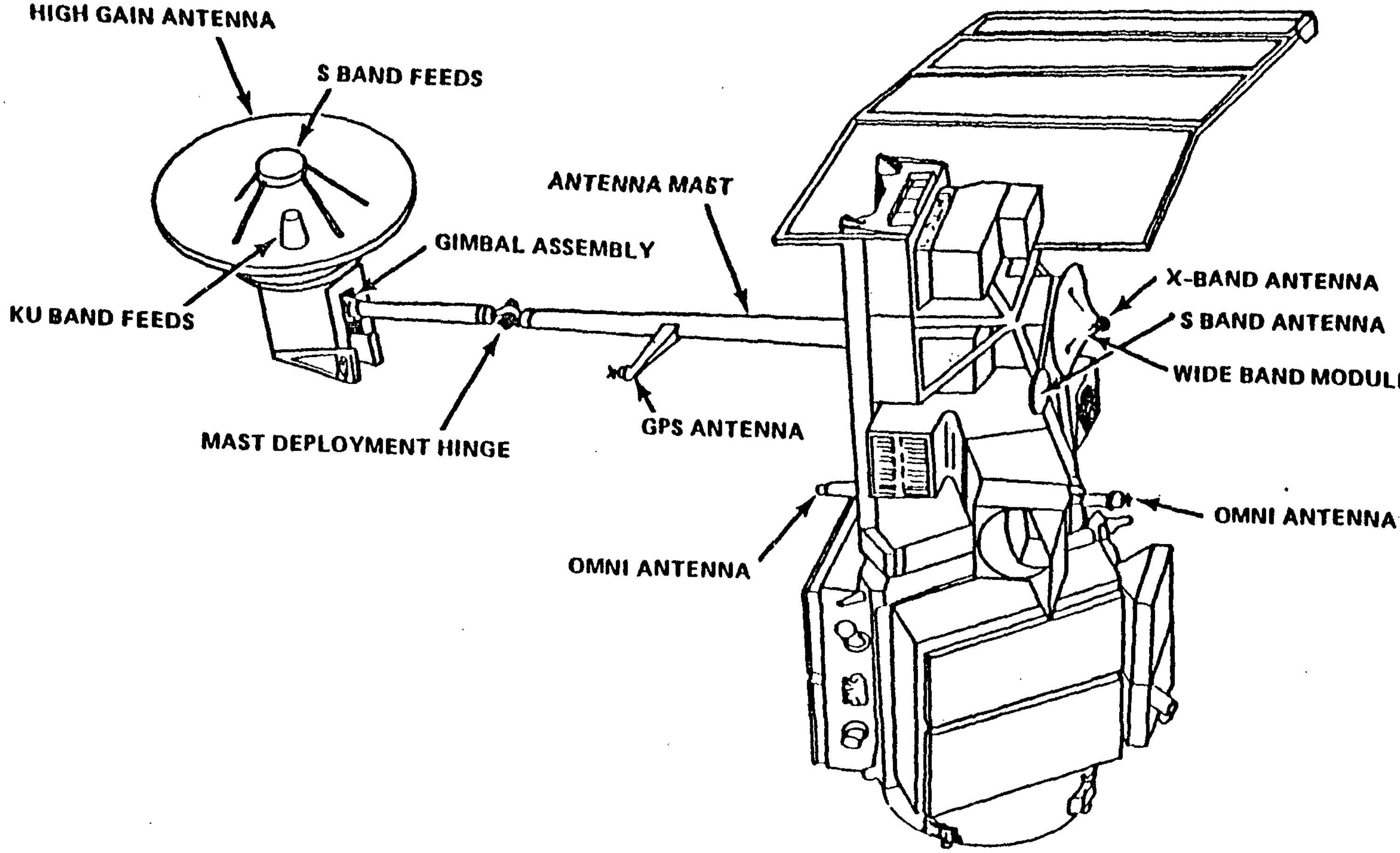


Figure 5-3. Landsat D Antenna Configurations

For KSA/TDRS transmission a modulated S-band signal is applied to the Ku-band converter contained in the RF compartment. The upconverters, driven from references provided from the wideband module frequency generator, upconvert the modulated S-band signal to the Ku-band. The output from the upconverter is amplified by means of a 20 watt TWTA before being filtered by transmit filters.

5.2 ASSUMPTIONS AND GROUND RULES

Alternatives for Landsat D telecommunications when they not available from TDRSS are considered on the basis of the following assumptions and ground rules.

5.2.1 GENERAL

There are two fundamental mechanisms which might cause Landsat D not to obtain communications services from TDRSS:

a. Satellite is in the Zone of Exclusion (ZOE) from where neither TDRS-E or TDRS-W can be seen (line of sight between user satellite and TDRS is obscured by the Earth). These periods can exceed 20 minutes.

b. Satellite is in a "TDRS is busy zone", where busy is a function of user priority.

This indicated that in addition to the systematic ZOE user priority may pre-empt TDRSS services resulting in the non-availability of Landsat D transmission of image data (TM and MSS), telemetry, command and ranging data.

5.2.2 PRIMARY FUNCTIONS OF THE LANDSAT FLIGHT SEGMENT

The formation of images of the Earth in electronic form (data) generated by the TM and MSS instruments is fundamental to the Landsat D mission.

Landsat provides RF links to transmit data sets which represent images (TM and MSS) both directly to the ground and by means of TDRSS.

In order to form and translate into the MSS and TM image format, instrument pointing (optical line of sight) data, altitude and data on stability control of the space platform must be provided.

Landsat also generates data which represents an accounting of the vital flight segment functions. Data types, rates, formats, and RF links are described in detail in Table 5-1 (telecommunications without operational TDRSS) and Table 5-2 (telecommunications using TDRSS).

5.2.3 FUNCTIONS OF LANDSAT FLIGHT SEGMENT INTERFACES

Considering the Landsat D overall data flow without operational TDRSS as shown in Figure 5-1, the data management system (DMS) receives the TM and MSS instrument data through a transportable ground station (TGS) located at GSFC and connected to the DMS. Telemetry from the spacecraft is also received through GSTDN stations located at Goldstone and in Alaska, where it is tape recorded and played back through a DOMSAT link to a ground terminal at GSFC. When TDRSS is operational, the overall Landsat D data flow, as shown in Figure 5-2, starts at the steerable spacecraft antenna, is relayed by one of the two TDRS's to be received at the TDRSS ground terminal at White Sands, N.M., where it is processed and recorded for transmission through a DOMSAT link to a DOMSAT Earth station at GSFC, from where it is then routed to the DMS.

The operations control center (OCC), as a major element of the Landsat system ground segment, receives telemetry and provides commands via S-band transmission to Landsat through TDRSS or GSTDN uplinks.

If properly equipped, foreign users (ground stations not owned by NASA) could receive direct transmissions at X-band of TM and MSS data and at S-band MSS data similarly to that available from Landsat 3.

5.2.4 PHASE DOWN OF GSTDN

The NASA ground spaceflight tracking and data network, which has provided the telecommunications services for Landsat 1, 2, and 3, will be gradually phased down following the completion of integration of TDRSS into STDN. This integration has already begun with compatibility testing, and further tests to be performed on TDRS-A. TDRSS service availability will be achieved in two steps: (1) single-satellite system - 3 months after TDRS-A

launch, providing partial coverage, and (2) two-satellite system - 3 months after TDRS-B launch that is, October 1983 based on current launch schedules.

GSTDN will provide ground segment telecommunications support for Landsat D until TDRSS becomes available. The Landsat D support provides telecommunications coverage to meet the mission design, including all available contacts of the three prime ground stations (BLT, GDS, and ULA). Support for TLM, CMD, TRK, and MSS imaging operations will be provided. GSTDN coverage requirements for Landsat are expected to be linked to operations necessary for checkout, orbit adjustment, and any required station keeping functions prior to the start of full TDRSS operational support. Additional TLM, CMD, and TRK support from other GSTDN stations will be requested to supplement the coverage of prime stations with a maximum of 17 contacts of 15 minutes each expected per day. BLT does not currently perform MSS imaging operations. Image data will be received by the project-operated Transportable Ground Station (TGS) which is located near the GSFC Building 28.

The current STDN station closure plan indicates that the STDN ground stations which support Landsat D and D' will be closed in accordance with the following schedule.

STDN GROUND STATION CLOSURES

STATION	DATE
FAIRBANKS (ULA)	10-'84
GOLDSTONE (GDS)	02-'85
GREENBELT (BLT)	10-'88

The effects on the STDN phase down on the Landsat D mission could include:

- Increasing total dependence on TDRSS telecommunication services, without communications backup.
- Uplink command and ranging data no longer available, except via TDRSS.
- Substitution of a relatively operationally unproven space relay telecommunications system for the operationally proven GSTDN.
- Landsat D and D' have been equipped to interface with GSTDN, which will become useless when GSDTN is phased down.

- NASA may be able to offset TDRSS operational cost by the cost avoidance resulting from the GSTDN phase down.
- Centralization of data management, spacecraft command and data product distribution.

5.3 IDENTIFICATION OF TELECOMMUNICATION ALTERNATIVES FOR LANDSAT MISSION UTILIZATION

In section 5.2.1, the systematic zone and been the "TDRS is busy" zone of exclusion have identified as the periods during which TDRSS services are not available to Landsat. The next three subsections of this report discuss alternatives, or work arounds to temporary interruptions of the TDRSS real-time data satellite to ground communications. The alternatives which are discussed are consistent with the assumptions and ground rules identified in section 5.2.

5.3.1 THIRD TDRS IN ORBIT

Placing a third or spare TDRS in orbit will increase the number of single access (KSA) links from 4 to 6 (50% increase). This alternative could reduce the "TDRS is busy" zone, as illustrated by comparing Figure 5-4 and Figure 5-5, which Landsat will experience when TDRS-E is busy servicing higher priority users. Figure 5-4 shows the ZOE where TDRS-E is not available while Figure 5-5 illustrates that an up to 50% reduction in "TDRS-E is busy" zone can be provided by a third TDRSS, assumed, for the example shown, to be located at 106^{o}W, midway between TDRS-E and TDRS-W. Similarly, the ZOE (Figure 5-6) where "TDRS-W is busy" can be reduced to the ZOE shown in Figure 5-7. Thus "TDRS is busy" zone might be reduced up to 50%, but a third TDRS will not eliminate it or have any affect on the systematic ZOE. This alternative will be very expensive and decrease the TDRSS throughput efficiency, unless the satellite system is overloaded in the first place.

5.3.2 USE OF ON-BOARD WIDEBAND TAPE RECORDERS

Previous Landsats have been equipped with wide-band tape recorders which permitted MMS imaging data storage independent of real-time telecommunications availability. With the increased imaging capability of the Thematic Mapper (TM) which produces imaging data at approximately 85 Mbps,

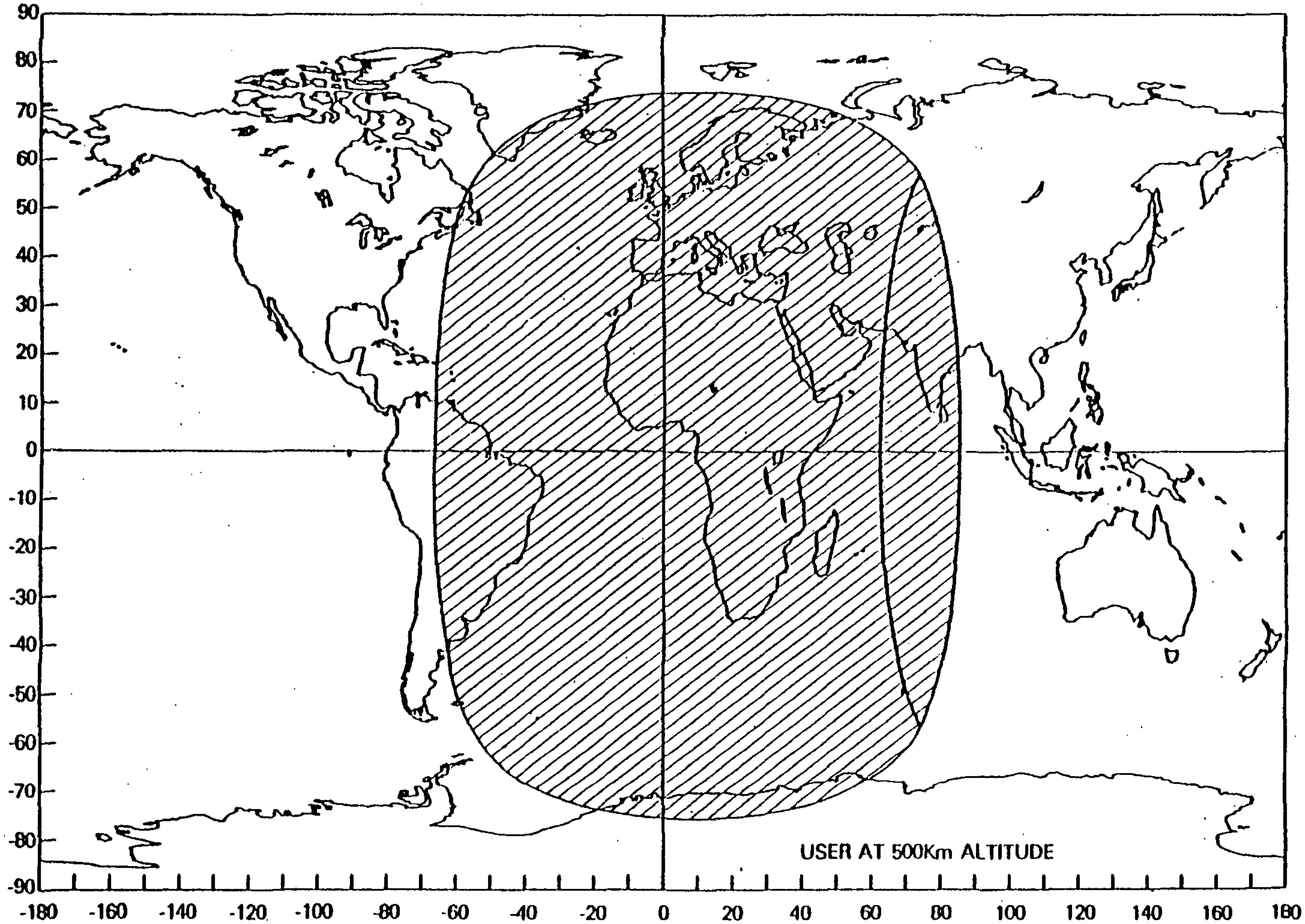


Figure 5-4. ZOE if Two TDRS's are in Orbit and TDRS-E is Busy Serving Higher Priority Users

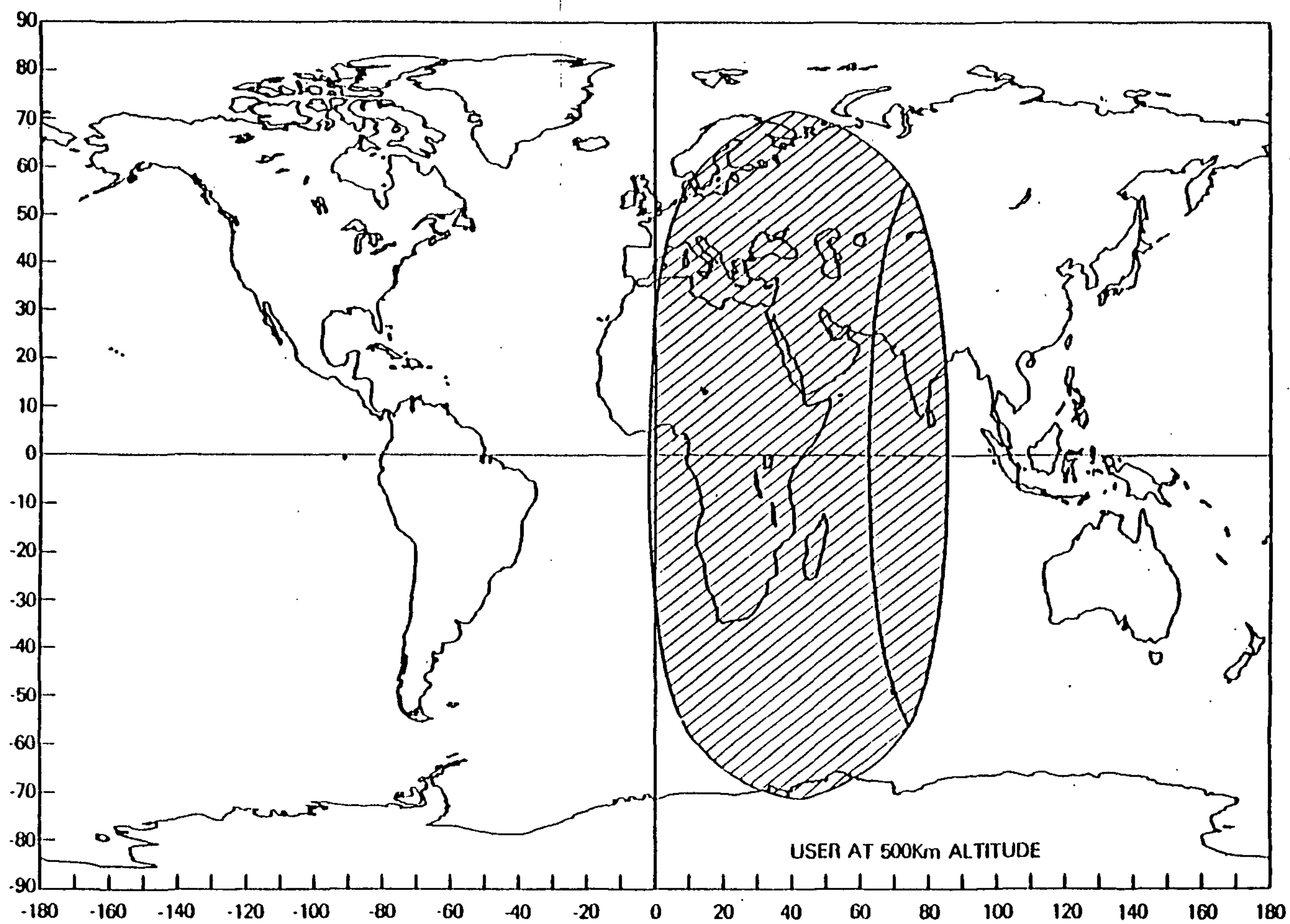


Figure 5-5. ZOE If Three TDRS's Are In Orbit & TDRS-E Is Busy Serving Higher Priority Users

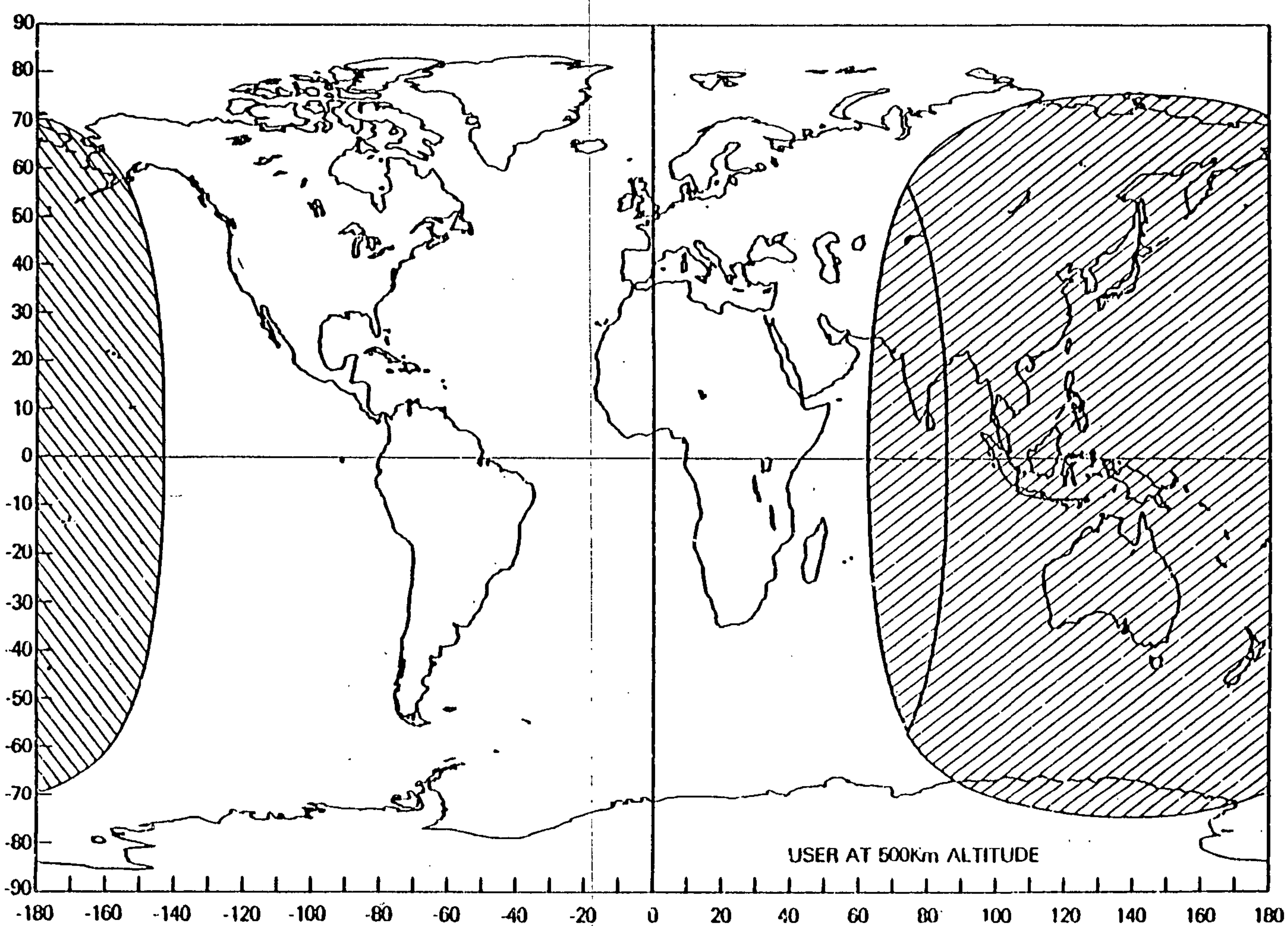


Figure 5-6. ZOE if Two TDRS's are in Orbit and TDRS-W is Busy Serving Higher Priority Users

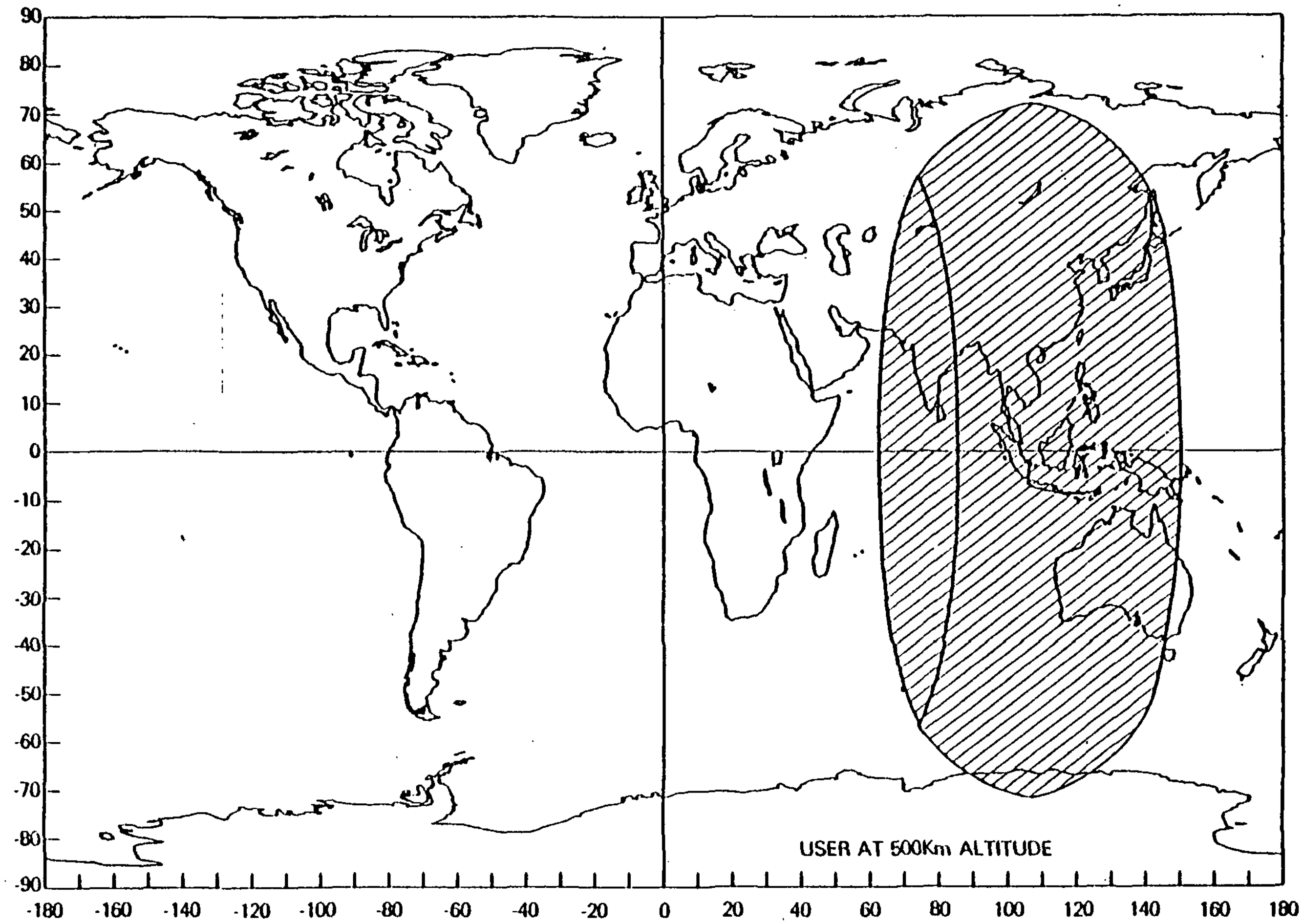


Figure 5-7. ZOE if Three TDRS's are in Orbit and TDRS-W is Busy Serving Higher Priority Users

currently available space-qualified tape machines could neither record at these rates nor have sufficient storage capacity.

An onboard wideband tape recorder can eliminate the systematic ZOE of the two-satellite TDRSS and a telecommunications priority imposed ZOE. This advantage of the on board tape recorder telecommunication alternative can be achieved only by considering the following baseline requirements which must be met.

- Store MSS and TM data for delayed transmission to ground. (MSS - 1.3×10^8 bits/image; TM - 1.84×10^9 bits/image).
- Recording speed must be comparable with data rates to be transmitted (MSS - 15 Mbps; TM - 85 Mbps).
- Recording (onboard storage) capacity must be sufficient to hold data that cannot be transmitted in real time (10^{10} to 10^{11} bits).

Other parameters which must be considered for a mass storage system for space applications are reliability, weight, volume, speed range, bit error rate and of course, cost. Currently no space qualified wideband tape recorders are available for near-term use (Landsat D[1] application). However, NASA's Office of Tracking and Data Systems currently supports the developemnt of (1) advanced technology (i.e., tapes, heads, tape guides, coding, etc.), (2) a 20 Mbps tape recorder, and (3) a 150 Mbps tape recorder. The characteristics of these tape recorders are summarized in Table 5-3. During the last weeks the procurement phase of the 20 Mbps tape recorder development has been completed with the award of a design and development contract leading to a qualification test by the end of FY'84 and life cycle tests complete in the third quarter of FY'85. Based on this schedule, flight units would be available by late FY'86.

The 150 Mbps system development has been started with the initiation of the procurement. Recently FY'83 funding has been delayed apparently as a result of lacking TDRSS user interest in this technology. The plan for this development had targeted the second quarter of FY'86 for qualification tests, followed by the completion of life cycles test one year later (FY'87) and flight hardware availability by the middle of FY'88. This schedule and particularly funding delays have moved the possible availability of wide-band tape recorders way beyond the anticipated

Table 5-3. Onboard Wideband Tape Recorder Baseline Characteristics

CHARACTERISTICS		
DATA RATES	20 MPBS	150 MBPS
RECORD	5 TO 20 MBPS	10 to 150 MBPS
REPRODUCE	10 TO 20 MBPS	50 TO 150 MBPS
CAPACITY	10^{10} BITS	11^{11} BITS
BIT ERROR RATE (BER)	10^{-5} TO 10^{-7}	10^{-5} TO 10^{-7}
WEIGHT	45 LBS	125 LBS
POWER	40-75 WATTS	100-250 WATTS
VOLUME	1 CUBIC FOOT	3 CUBIC FEET
LIFE	20,000 PASSES	20,000 PASSES
SCHEDULE		
QUALIFIED UNIT	FY'84	FY'86
FLIGHT UNIT	FY'86	FY'87

Landsat D' launch date. However, there is a possibility that this equipment might be available for a mission beyond Landsat D'.

In summary, in spite of the advantageous capabilities of on board wide-band tape recorders which provide for the elimination of both the (TDRSS) systematic and telecommunications priority imposed zones of exclusion, the disadvantages of availability, large recurring cost, and risk do not give much hope for this alternative for Landsat telecommunications.

5.3.3 UTILIZATION OF GSTDN

In Sections 5.1.1 and 5.1.2 it was shown that Landsat D is equipped to communicate directly with the Earth independently of TDRSS. Therefore, even when TDRSS is fully operational, the "Non TDRSS" elements of Landsat D's telecommunications on board system are providing inherent downlink capabilities. Accepting that the "Non TDRSS" space segment of the Landsat D telecommunication system is available the ground segment capable of receiving Landsat D telecommunications is listed in the following table:

	BLT	GDS	MAD	ORR	ULA	TGS	FOREIGN
S-BAND CMD	X	X	-	-	X	-	X
S-BAND TLM	X	X	-	-	X	X	X
S-BAND TRK	X	X	-	-	X	-	X
S-BAND TLM IMAGE	X	X	-	-	X	-	X
KU-BAND TLM IMAGE	-	-	-	-	-	X	-
X-BAND TLM IMAGE	-	-	-	-	-	X	-

The above information shows that at this time (GSTDN is still fully operational) and there is no single ground station equipped to receive all data in one location to support the Landsat D mission at the same level as TDRSS. However, the total "Non TDRSS" capabilities can be satisfactory as an alternative for TDRSS as will be discussed next.

From the above table the GSTDN stations Greenbelt (BLT), Goldstone (GDS), Fairbanks (ULA) and many foreign (non-NASA) facilities are capable of receiving MSS and TLM data from Landsat 3. Since the MSS system of Landsat D is identical to that of "3", the previously listed GSTDN stations can handle Landsat D MSS image data also.

The TM image data can be transmitted in the "Non TDRSS" configuration over X-band directly to the ground. Currently NASA-GSFC operates a transportable ground station (TGS) which is capable of receiving the TM image data. The required X-band receiving technology is commercially available, permitting existing GSTDN and foreign ground stations to be equipped for the reception of TM data without TDRSS services.

A subset of the above described "Non-TDRSS" Landsat D telecommunication alternative is discussed next. As mentioned earlier, ground station technology to receive S-band TLM data is available at many STDN terminals. This S-band link (2265.5 Mhz) has sufficient bandwidth for the transmission of digital MSS TLM data at 15.0626 Mbps. This indicates that this S-band link has a bandwidth in excess of 15 MHz.

The TM data is being transmitted at 84.903 Mbps. However, this data (TM) is being sensed as a video (analog) signal, which is sampled at a rate slightly higher than the Nyquist rate then the sampled video is quantized to 8 bits and serialized into the 84.903 Mbps digital representation. Reversing this process indicates that the equivalent (analog) bandwidth of the TM data appears to be in the order of 5.0 MHz. This suggests that it might be possible to transmit TM analog data in S-band over the RF link which is used for MSS TLM data. In addition data apparently could be stored in orbit on existing analog tape recorders.

These alternatives provide the following advantages:

- Low cost and utilization of existing technology

- Minor modification of the Landsat D system (to be verified by detailed analysis).

- Minor modifications of STDN and foreign ground stations to receive TM imagery with minimal effort.

- Expansion of the Landsat user community independent of TDRSS.
- A back-up approach for Landsat D when TDRSS is not available.
- Earth coverage is a function of Earth station line of sight availability.
- Direct Landsat to ground station communications.
- Lower transmitter power requirements.

The "Non-TDRSS" alternative telecommunications approach is likely to have some disadvantages.

- Possible deletion of NASA's control of access to TM and MSS image data.
- Coverage is limited by the visibility cone and antenna tracking requirement.
- Reactivation of GSTDN.
- Lower signal quality for fixed power at the receiver.
- Lowered bit error rate.
- Duplication of facilities and operational expenses.
- Does not permit utilization of bandwidth compression techniques.
- Lessened utilization of advanced digital technology.
- No influence on X-band foreign station upgrade.

In summary, the possible utilization of the TM and MSS video signals appears to have merit as a viable telecommunications alternative to TDRSS for Landsat D-type missions. It is, however, recommended that this alternative be subjected to an in-depth engineering analysis to validate feasibility, and to verify the impact of the approach.

GLOSSARY

ADDS	Applications Development Data System
BiØ	Bi-phase
BLT	Greenbelt (STDN Station)
C&T	Communications and Tracking
CMD	Command
CTV	Compatability Test Van
DMS	Data Management System
DOMSAT	Domestic Communications Satellite
DSN	Deep Space Network
EDC	EROS Data Center, Sioux Falls, SD
FM	Frequency Modulation
GDS	Goldstone, CA (STDN Station)
GSFC	Goddard Space Flight Center, Greenbelt, MD
IRIG	Interrange Instrumentation Group
JSC	Johnson Space Center, Houston, TX
Ku-band	10.90 to 17.15 GHz
KSA	K-band Single Access
LAS	Landsat D Assessment System
MA	Multiple Access
MPT	Mission Planning Terminal
MSS	Multispectral Scanner
NASCOM	NASA Communication Network
NBTR	Narrow-Band Tape Recorder
NRZ-L	Nonreturn to Zero-Level

NRZ-M	Nonreturn to Zero-Mark
NTTF	Network Test and Training Facility
OCC	Operations Control Center
OPS	Operations
OSCF	Operations Support Computing Facility
PCD	Payload Corrective Data
PCM	Pulse Code Modulation
PN	Pseudo Noise
POCC	Project (or Payload) Operations Control Center
RF	Radio Frequency
REC	Receive
SA	Single Access
SIRD	Support Instrumentation Requirements Document
SOC	Simulations Operations Center
SQPSK	Staggered Quadrature Phase-Shift Keyed
SSA	S-band Single Access
TDRSS	Tracking and Data Relay Satellite System
TLM	Telemetry
TM	Thematic Mapper
TWTA	Traveling-wave Tube Amplifier
TWX	Teletype
TX	Transmit
UQPSK	Unbalanced Quadrature Phase-Shift Keyed
ULA	Fairbanks, Alaska (STDN Station)
VF	Valley Forge

WRS	Worldwide Reference System
X-band	8000 to 10,999 MHz
ZOE	Zone of Exclusion

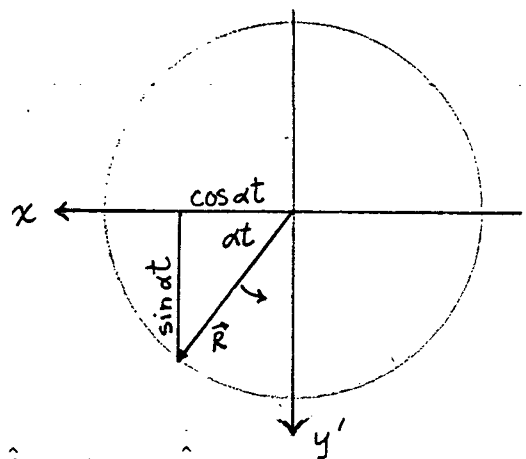
APPENDIX A.

ANALYSIS FOR CIRCULAR ORBIT CALCULATIONS

APPENDIX A

ANALYSIS FOR CIRCULAR ORBIT CALCULATIONS

Assume a rotating unit vector in an x-y plane.

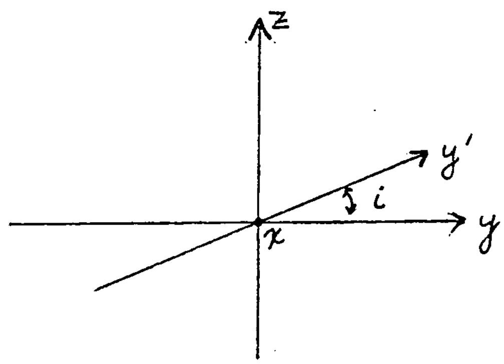


(1) $\vec{R}_1 = \cos \alpha t\, \hat{i} + \sin \alpha t\, \hat{j}$

where α = angular velocity (radians/min) in CCW direction

t = time in minutes

We now require that the plane of this rotating Vector be inclined by the angle i to a stationary geocentric x-y reference plane.



Using the rotational matrix, we have

$$\vec{R}_2 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos i & -\sin i \\ 0 & \sin i & \cos i \end{bmatrix} \begin{bmatrix} \cos \alpha t \\ \sin \alpha t \\ 0 \end{bmatrix}$$

which gives

(2) $\vec{R}_2 = \cos \alpha t \, \hat{i} + \cos i \sin \alpha t \, \hat{j} + \sin i \sin \alpha t \, \hat{k}$

We now account for the Earth's rotation by describing $\vec{R}_2$ in terms of the rotating geocentric axis. Again, using the rotational matrix

$$\vec{R}_2 = \begin{bmatrix} \cos \omega t & \sin \omega t & 0 \\ -\sin \omega t & \cos \omega t & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos \alpha t \\ \cos i \sin \alpha t \\ \sin i \sin \alpha t \end{bmatrix}$$

This gives

(3) $\vec{R} = x \, \hat{i} + y \, \hat{j} + z \, \hat{k}$

where

(3a) $x = \cos \omega t \cos \alpha t + \sin \omega t \cos i \sin \alpha t$

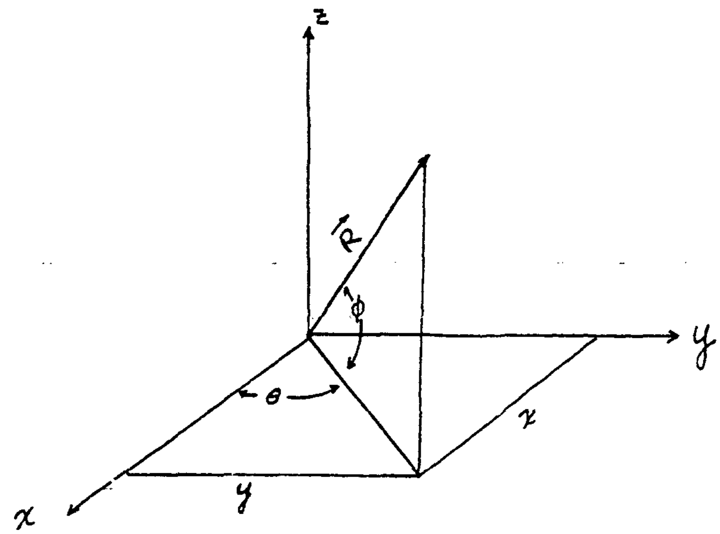
(3b) $y = -\sin \omega t \cos \alpha t + \cos \omega t \cos i \sin \alpha t$

(3c) $z = \sin i \sin \alpha t$

and

ω = angular velocity of rotating geocentric reference frame

It is now necessary to describe the rotational unit vector in terms of polar coordinates (latitude, longitude)



The latitude, ϕ , is obtained using equation 3c.

$$R \sin \phi = t = \sin i \sin \alpha t$$

$$\phi = \arc\sin (\sin i \sin \alpha t) \tag{4}$$

The longitude, θ, is obtained using equations 3a and 3b.

$$\theta = \arc\tan ({}^{y}/x)$$

$$\theta = \arc\tan \left(\frac{-\sin \omega t \cos \alpha t + \cos \omega t \cos i \sin \alpha t}{\cos \omega t \cos \alpha t + \sin \omega t \cos i \sin \alpha t}\right) \tag{5}$$

APPENDIX B.

BASIC LISTING OF CIRCULAR ORBIT PROGRAM

LANDSAT-D ORBIT & TDRSS COVERAGE PROGRAM

```
10 PRINT "ALIGN PAPER.  PRESS ANY KEY.  "
20 GET WT$ : IF WT$=""  GOTO 20
30 OPEN 1,4:OPEN 2,4,3
35 A$="LANDSAT-D ORBIT & TDRSS COVERAGE PROGRAM"
40 PRINT#1,CHR$(1) A$:PRINT#1:PRINT#1: CLOSE 1
50 PRINT#2,CHR$(147):CLOSE 2
60 A1=107.103:DR=3.1415927/180
70 I=98.21:OA=705.3:J=.00108265:B1=-41.0:B2=-171.0:B$=" ":C$=" ":RE=6378.388
80 K=398575:L1=319:L2=181:A2=OA+RE:PI=3.1415927
83 T1 =PI/30*SQR((A2↑3)/K):W1=2*PI/T1
85 W2=(-1.5*J*SQR(K/A2↑3)*RE/A2↑2)/1440
88 W3=(.25 -W2)*DR
89 N=19
90 OPEN 4,4
100 PRINT#4,"THESE ARE THE VALUES AND CONSTANTS USED:"
110 PRINT#4,"     EARTH RADIUS IS";RE;"KM"
120 PRINT#4,"     ORBIT ALTITUDE IS";OA;"KM"
130 PRINT#4,"     TDRSS-E IS AT";B1;"DEG LONG"
140 PRINT#4,"     TDRSS-W IS AT";B2;"DEG LONG"
150 PRINT#4,"     ORBIT  INCLINATION IS";I;"DEGREES"
160 PRINT#4,"     GRAVITATIONAL CONSTANT IS";K;"KM CUBED/SEC SQUARED"
162 PRINT#4,"     ORBITAL PERIOD IS";T1;"MIN"
164 PRINT#4,"     ORBITAL PRECESSION RATE IS";W2;"RAD/MIN"
166 PRINT#4,"     RELATIVE EARTH ANGULAR VELOCITY IS";W3;"DEG/MIN"
170 PRINT#4:PRINT#4:PRINT#4:CLOSE 4
210 X1=COS(L1*DR):Y1=SIN(L1*DR):Z1=0
220 X2=COS(L2*DR):Y2=SIN(L2*DR):Z2=0
230 OPEN 2,4,2:OPEN 4,4:OPEN 6,4,1
240 F$="          ORBIT NO    DAY-HR-MIN    LAT     LONG     TDRSS-E     TDRSS-W"
250 PRINT#4,F$
260 G$="             999         99  99  99  S999.9  S999.9       A            A"
270 PRINT#2,G$
280 FOR T=0 TO 233*T1 STEP T1/20
290 X3=COS(W1*T)*COS(W3*T)+SIN(W1*T)*SIN(W3*T)*COS(I*DR)
300 Y3=-COS(W1*T)*SIN(W3*T)+SIN(W1*T)*COS(W3*T)*COS(I*DR)
310 Z3=SIN(W1*T)*SIN(I*DR)
320 N=N+1:  M=INT(N/20)
330 DA=INT(T/1440):HR=INT((T-1440*DA)/60):MN=T-1440*DA-60*HR
340 A3=X2*X3+Y2*Y3+Z2*Z3
350 IF A3>COS(A1*DR) THEN C$="*"
360 A4=X1*X3+Y1*Y3+Z1*Z3
370 IF A4> COS(A1*DR) THEN B$="*"
380 LA=(ATN(Z3/SQR(1-Z3*Z3)))/DR
390 LN=(ATN(Y3/X3))/DR
400 IF X3>0 AND Y3<0 THEN LN=360 +LN
410 IF X3<0 AND Y3<0 THEN LN=180 +LN
420 IF X3<0 AND Y3>0 THEN LN=180 +LN
430 DEF FNA(X)=INT(X*10+.5)/10
450 PRINT#6,M,DA,HR,MN,FNA(LA),FNA(LN),B$,CHR$(29),C$
460 B$=" " : C$=" "
470 NEXT T
480 CLOSE 2 : CLOSE 4 : CLOSE 6
490 END
READY.
```

LANDSAT-D ORBIT & TDRSS COVERAGE PROGRAM

THESE ARE THE VALUES AND CONSTANTS USED:

EARTH RADIUS IS 6378.388 KM
ORBIT ALTITUDE IS 705.3 KM
TDRSS-E IS AT-41 DEG LONG
TDRSS-W IS AT-171 DEG LONG
ORBIT INCLINATION IS 98.21 DEGREES
GRAVITATIONAL CONSTANT IS 398575 KM CUBED/SEC SQUARED
ORBITAL PERIOD IS 98.8923585 MIN
ORBITAL PRECESSION RATE IS-1.51801066E-13 RAD/MIN
RELATIVE EARTH ANGULAR VELOCITY IS 4.3633232E-03 DEG/MIN

ORBIT NO	DAY-HR-MIN			LAT	LONG	TDRSS-E	TDRSS-W
1	0	0	0	+ .0	+ .0	*	
1	0	0	4	+ 17.8	+356.1	*	
1	0	0	9	+ 35.6	+351.6	*	
1	0	0	14	+ 53.2	+345.2	*	
1	0	0	19	+ 70.3	+331.3	*	*
1	0	0	24	+ 81.8	+263.8	*	*
1	0	0	29	+ 70.3	+196.3	*	*
1	0	0	34	+ 53.2	+182.5		*
1	0	0	39	+ 35.6	+176.0		*
1	0	0	44	+ 17.8	+171.5		*
1	0	0	49	+ .0	+167.6		*
1	0	0	54	- 17.8	+163.7		*
1	0	0	59	- 35.6	+159.2		*
1	0	1	4	- 53.2	+152.8		*
1	0	1	9	- 70.3	+139.0		*
1	0	1	14	- 81.8	+ 71.5	*	*
1	0	1	19	- 70.3	+ 3.9	*	
1	0	1	24	- 53.2	+350.1	*	
1	0	1	29	- 35.6	+343.7	*	
1	0	1	33	- 17.8	+339.2	*	
2	0	1	38	+ .0	+335.3	*	
2	0	1	43	+ 17.8	+331.4	*	
2	0	1	48	+ 35.6	+326.9	*	
2	0	1	53	+ 53.2	+320.4	*	
2	0	1	58	+ 70.3	+306.6	*	*
2	0	2	3	+ 81.8	+239.1	*	*
2	0	2	8	+ 70.3	+171.6	*	*
2	0	2	13	+ 53.2	+157.7		*
2	0	2	18	+ 35.6	+151.3		*
2	0	2	23	+ 17.8	+146.8		*
2	0	2	28	+ .0	+142.9		*
2	0	2	33	- 17.8	+139.0		*
2	0	2	38	- 35.6	+134.5		*
2	0	2	43	- 53.2	+128.1		*
2	0	2	48	- 70.3	+114.2		*
2	0	2	53	- 81.8	+ 46.7	*	*
2	0	2	58	- 70.3	+339.2	*	
2	0	3	2	- 53.2	+325.4	*	
2	0	3	7	- 35.6	+318.9	*	

APPENDIX C.

FORTRAN LISTING OF CIRCULAR ORBIT PROGRAM

```
VAX/VMS  LEN        TDRSS     5-OCT-1981 14:57    LPA0:   5-OCT-1981 14:57    _DBA0:[LEN]TDRSS.LIS;12   VAX/VMS
VAX/VMS  LEN        TDRSS     5-OCT-1981 14:57    LPA0:   5-OCT-1981 14:57    _DBA0:[LEN]TDRSS.LIS;12   VAX/VMS
VAX/VMS  LEN        TDRSS     5-OCT-1981 14:57    LPA0:   5-OCT-1981 14:57    _DBA0:[LEN]TDRSS.LIS;12   VAX/VMS
```

LEN

TDRSS.

LIS;12

LEN

```
VAX/VMS  LEN        TDRSS     5-OCT-1981 14:57    LPA0:   5-OCT-1981 14:57    _DBA0:[LEN]TDRSS.LIS;12   VAX/VMS
VAX/VMS  LEN        TDRSS     5-OCT-1981 14:57    LPA0:   5-OCT-1981 14:57    _DBA0:[LEN]TDRSS.LIS;12   VAX/VMS
VAX/VMS  LEN        TDRSS     5-OCT-1981 14:57    LPA0:   5-OCT-1981 14:57    _DBA0:[LEN]TDRSS.LIS;12   VAX/VMS
```

```
C
C       LEN HARRIS' LANDSAT-D ORBIT AND TDRSS COVERAGE PROGRAM.
C       TRANSLATED FROM PET BASIC BY W. STRATTON, 9/30/81.
C
        REAL*4 A1,DR,I,OA,J,B1,B2,RE,K,A2,PI,T1,W1,W2,W3,X1,X2,X3
        REAL*4 Y1,Y2,Y3,Z1,Z2,Z3,T,A3,A4,LA,LN,FNA,ORBITS
        INTEGER*4 L1,L2,N,M,DA,HR,MN
        CHARACTER*1 BSTR,CSTR,ANSWER

        FNA(X)=NINT(X*10.)/10.
C
C       GET VARIABLES FOR THIS RUN
C
1       WRITE(5,2)
2       FORMAT(' ENTER I, OA, ORBITS, ONE VALUE PER LINE:')
        READ(5,3)I,OA,ORBITS
3       FORMAT(2(F12.5/),F12.5)
        WRITE(5,4)I,OA,ORBITS
4       FORMAT(' I=',G12.5,'         OA=',G12.5,'         ORBITS=',G12.5/
     1         ' ARE THESE VALUES CORRECT?')
        READ(5,5) ANSWER
5       FORMAT(A1)
        IF (ANSWER.NE.'Y') GOTO 1
C
C       INITIALIZE CONSTANTS
C
        A1 = 107.103
        DR = 3.1415927/180.
        J = .00108265
        B1 = -41.0
        B2 = -171.0
        RE = 6378.388
        K = 398575.
        L1 = 319
        L2 = 181
        A2 = OA + RE
        PI = 3.1415927
        T1 = PI/30. * SQRT((A2**3)/K)
        W1 = 2.*PI/T1
        W2 = (-1.5 * J * SQRT(K/A2**3) * RE/A2**2) / 1440.
        W3 = (.25 - W2) * DR
        N = 1
C
C       PRINT VALUES
C
        WRITE(6,10) RE,OA,B1
        WRITE(6,11) B2,I,K
        WRITE(6,12) T1,W2,W3
        WRITE(6,13)
10      FORMAT('1THESE ARE THE VALUES AND CONSTANTS USED:'/
     1  '      EARTH RADIUS IS                    ',G12.5,' KM'/
     2  '      ORBIT ALTITUDE IS                  ',G12.5,' KM'/
     3  '      TDRSS-E IS AT                      ',G12.5,' DEG LONG')
11    FORMAT('      TDRSS-W IS AT                      ',G12.5,
     1' DEG LONG'/'      ORBIT INCLINATION IS                ',G12.5,
     2' DEGREES'/'     GRAVITATIONAL CONSTANT IS          ',G12.5,
```

is only valid for Landsat

needs to be corrected

$$A1 = 81.317 + \cos^{-1}\left(\frac{RE}{OA+RE}\right) + \cos^{-1}\left(\frac{RE}{A2}\right)$$

```
                3' KM CUBED/SEC SQUARED')
0037     12        FORMAT('      ORBITAL PERIOD IS                    ',G12.5,
                1' MIN'/'    ORBITAL PRECESSION RATE IS           ',G12.5,
                2' RAD/MIN'/'      RELATIVE EARTH ANGULAR VELOCITY IS ',G12.5,
                3' RAD/MIN')
0038     13        FORMAT(////11X,'ORBIT NO',4X,'DAY-HR-MIN',4X,'LAT',4X,'LONG',4X,
                1      'TDRSS-E',4X,'TDRSS-W'/)
         C
         C         SET UP FOR LOOP
         C
0039               X1 = COS(L1*DR)
0040               Y1 = SIN(L1*DR)
0041               Z1 = 0.

0042               X2 = COS(L2*DR)
0043               Y2 = SIN(L2*DR)
0044               Z2 = 0.
         C
         C         MAIN LOOP
         C
0045               DO 100 T = 0., ORBITS * T1, T1/20.

0046               BSTR = ' '
0047               CSTR = ' '

0048               X3 = COS(W1*T)*COS(W3*T) + SIN(W1*T)*SIN(W3*T)*COS(I*DR)
0049               Y3 = -COS(W1*T)*SIN(W3*T) + SIN(W1*T)*COS(W3*T)*COS(I*DR)
0050               Z3 = SIN(W1*T)*SIN(I*DR)

0051               N = N+1
0052               M = N/20

0053               DA = IFIX(T/1440.)
0054               HR = IFIX((T - 1440.*DA)/60.)
0055               MN = IFIX(T - 1440.*DA - 60.*HR)

0056               A3 = X2*X3 + Y2*Y3 + Z2*Z3
0057               IF (A3.GT.COS(A1*DR)) CSTR = '*'
0058               A4 = X1*X3 + Y1*Y3 + Z1*Z3
0059               IF (A4.GT.COS(A1*DR)) BSTR = '*'

0060               LA = (ATAN(Z3/SQRT(1.-Z3**2)))/DR
0061               LN = ATAN(Y3/X3)/DR
0062               IF (X3.GT.0. .AND. Y3.LT.0.) LN = LN + 360.
0063               IF (X3.LT.0. .AND. Y3.LT.0.) LN = LN + 180.
0064               IF (X3.LT.0. .AND. Y3.GT.0.) LN = LN + 180.

0065               WRITE(6,20) M,DA,HR,MN,FNA(LA),FNA(LN),BSTR,CSTR
0066     20        FORMAT(13X,I3,7X,3(I2,2X),2(F6.1,2X),4X,A1,9X,A1)

0067     100       CONTINUE          ! END DO LOOP

0068               GOTO 1            ! GO BACK FOR ANOTHER PASS

0069               END
```

```
PROGRAM SECTIONS

    NAME                          BYTES   ATTRIBUTES

  0 $CODE                          1224   PIC CON REL LCL   SHR   EXE   RD NOWRT LONG
  1 $PDATA                          805   PIC CON REL LCL   SHR NOEXE   RD NOWRT LONG
  2 $LOCAL                          204   PIC CON REL LCL NOSHR NOEXE   RD   WRT LONG

ENTRY POINTS

    ADDRESS   TYPE  NAME

  0-00000000        TDRSS$MAIN

STATEMENT FUNCTIONS

    ADDRESS   TYPE  NAME

  0-000004B7  R*4   FNA

VARIABLES

    ADDRESS   TYPE  NAME             ADDRESS   TYPE  NAME           ADDRESS   TYPE  NAME            ADDRESS   TYPE  NAME

  2-00000004  R*4   A1             2-00000028  R*4   A2           2-00000068  R*4   A3           2-0000006C  R*4   A4
  2-00000002  CHAR  ANSWER         2-00000018  R*4   B1           2-0000001C  R*4   B2           2-00000000  CHAR  BSTR
  2-00000001  CHAR  CSTR           2-0000008C  I*4   DA           2-00000008  R*4   DR           2-00000090  I*4   HR
  2-0000000C  R*4   I              2-00000014  R*4   J            2-00000024  R*4   K            2-0000007C  I*4   L1
  2-00000080  I*4   L2             2-00000070  R*4   LA           2-00000074  R*4   LN           2-00000088  I*4   M
  2-00000094  I*4   MN             2-00000084  I*4   N            2-00000010  R*4   OA           2-00000078  R*4   ORBITS
  2-0000002C  R*4   PI             2-00000020  R*4   RE           2-00000064  R*4   T            2-00000030  R*4   T1
  2-00000034  R*4   W1             2-00000033  R*4   W2           2-0000003C  R*4   W3          AP-00000004@ R*4   X
  2-00000040  R*4   X1             2-00000044  R*4   X2           2-00000048  R*4   X3           2-0000004C  R*4   Y1
  2-00000050  R*4   Y2             2-00000054  R*4   Y3           2-00000058  R*4   Z1           2-0000005C  R*4   Z2
  2-00000060  R*4   Z3

LABELS

    ADDRESS   LABEL      ADDRESS   LABEL      ADDRESS   LABEL      ADDRESS   LABEL      ADDRESS   LABEL      ADDRESS   LABEL

  0-00000009  1        1-00000000  2'       1-0000002C  3'       1-00000039  4'       1-00000084  5'       1-00000087  10'
  1-00000158  11'      1-00000214  12'      1-000002BE  13'      1-00000303  20'          **      100

FUNCTIONS AND SUBROUTINES REFERENCED

MTH$ATAN       MTH$COS        MTH$SIN        MTH$SQRT

TOTAL SPACE ALLOCATED = 2233 BYTES
```

```
COMMAND QUALIFIERS

  FORTRAN /LIS TORSS

  /CHECK=(NOBOUNDS,OVERFLOW)
  /DEBUG=(NOSYMBOLS,TRACEBACK)
  /F77  /NOG_FLOATING  /I4  /OPTIMIZE  /WARNINGS  /NOD_LINES  /NOMACHINE_CODE  /CONTINUATIONS=19

COMPILATION STATISTICS

  RUN TIME:           3.54 SECONDS
  ELAPSED TIME:       10.60 SECONDS
  PAGE FAULTS:        504
  DYNAMIC MEMORY:     58 PAGES
```

OAO CORPORATION